# Fire Protection for the Built Environment

FPBE-Student Manual

*1st Edition, 3rd Printing-August 2014*

FEMA

**FEMA/USFA/NFA**
**FPBE-SM**
**August 2014**
**1st Edition, 3rd Printing**

# *Fire Protection for the Built Environment*

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## U.S. DEPARTMENT OF HOMELAND SECURITY

## UNITED STATES FIRE ADMINISTRATION

## NATIONAL FIRE ACADEMY

## FOREWORD

The U.S. Fire Administration (USFA), an important component of the Department of Homeland Security (DHS), serves the leadership of this Nation as the DHS's fire protection and emergency response expert. The USFA is located at the National Emergency Training Center (NETC) in Emmitsburg, Maryland, and includes the National Fire Academy (NFA), National Fire Data Center (NFDC), and the National Fire Programs (NFP). The USFA also provides oversight and management of the Noble Training Center in Anniston, Alabama. The mission of the USFA is to save lives and reduce economic losses due to fire and related emergencies through training, research, data collection and analysis, public education, and coordination with other Federal agencies and fire protection and emergency service personnel.

The USFA's National Fire Academy offers a diverse course delivery system, combining resident courses, off-campus deliveries in cooperation with State training organizations, weekend instruction, and online courses. The USFA maintains a blended learning approach to its course selections and course development. Resident courses are delivered at both the Emmitsburg campus and the Noble facility. Off-campus courses are delivered in cooperation with State and local fire training organizations to ensure this Nation's firefighters are prepared for the hazards they face.

## PURPOSE

For many of you, this course may be your first exposure to the technical aspects of "fire prevention." You may have been handed a copy of our local fire code and told to go enforce it without any training or understanding of its purpose.

The purpose of this course is to introduce you to the many factors influencing fire protection in the built environment, as well as give you a fundamental understanding of how these factors may have evolved into or influenced the development of building and fire codes and standards.

Students who successfully complete this course should be able to apply their local building and fire codes with a solid background in how the codes were developed and the intent of their application. You will not be an instant expert in the application of codes and standards, or understanding the many subtleties of fire protection in the built environment, but you will be a more effective fire inspector once you understand the "why" and "how" this course provides.

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## COURSE SCHEDULE

| | |
|---|---|
| Unit 0: | Introduction and Course Overview |
| Unit 1: | Fire in America |
| Unit 2: | Fire Dynamics and the Built Environment |
| Unit 3: | Fire-Related Human Behavior |
| Unit 4: | Egress Concepts |
| Unit 5: | Active and Passive Fire Protection Systems |
| Unit 6: | Hazardous Materials: Recognition and Control |
| Unit 7: | Fire Modeling Concepts |

## FINAL EXAM

The final exam contains 62 questions: true-false, multiple choice, fill-in-the-blank, and short essay. It is open book, meaning you may use all of the resources in the classroom (excluding instructors and other students) to answer the questions. You must score 80 percent to pass.

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# Firefighter Code of Ethics

## Background

The Fire Service is a noble calling, one which is founded on mutual respect and trust between firefighters and the citizens they serve. To ensure the continuing integrity of the Fire Service, the highest standards of ethical conduct must be maintained at all times.

Developed in response to the publication of the Fire Service Reputation Management White Paper, the purpose of this National Firefighter Code of Ethics is to establish criteria that encourages fire service personnel to promote a culture of ethical integrity and high standards of professionalism in our field. The broad scope of this recommended Code of Ethics is intended to mitigate and negate situations that may result in embarrassment and waning of public support for what has historically been a highly respected profession.

Ethics comes from the Greek word ethos, meaning character. Character is not necessarily defined by how a person behaves when conditions are optimal and life is good. It is easy to take the high road when the path is paved and obstacles are few or non-existent. Character is also defined by decisions made under pressure, when no one is looking, when the road contains land mines, and the way is obscured. As members of the Fire Service, we share a responsibility to project an ethical character of professionalism, integrity, compassion, loyalty and honesty in all that we do, all of the time.

We need to accept this ethics challenge and be truly willing to maintain a culture that is consistent with the expectations outlined in this document. By doing so, we can create a legacy that validates and sustains the distinguished Fire Service institution, and at the same time ensure that we leave the Fire Service in better condition than when we arrived.

# Firefighter Code of Ethics

**I understand that I have the responsibility to conduct myself in a manner that reflects proper ethical behavior and integrity. In so doing, I will help foster a continuing positive public perception of the fire service. Therefore, I pledge the following…**

- Always conduct myself, on and off duty, in a manner that reflects positively on myself, my department and the fire service in general.
- Accept responsibility for my actions and for the consequences of my actions.
- Support the concept of fairness and the value of diverse thoughts and opinions.
- Avoid situations that would adversely affect the credibility or public perception of the fire service profession.
- Be truthful and honest at all times and report instances of cheating or other dishonest acts that compromise the integrity of the fire service.
- Conduct my personal affairs in a manner that does not improperly influence the performance of my duties, or bring discredit to my organization.
- Be respectful and conscious of each member's safety and welfare.
- Recognize that I serve in a position of public trust that requires stewardship in the honest and efficient use of publicly owned resources, including uniforms, facilities, vehicles and equipment and that these are protected from misuse and theft.
- Exercise professionalism, competence, respect and loyalty in the performance of my duties and use information, confidential or otherwise, gained by virtue of my position, only to benefit those I am entrusted to serve.
- Avoid financial investments, outside employment, outside business interests or activities that conflict with or are enhanced by my official position or have the potential to create the perception of impropriety.
- Never propose or accept personal rewards, special privileges, benefits, advancement, honors or gifts that may create a conflict of interest, or the appearance thereof.
- Never engage in activities involving alcohol or other substance use or abuse that can impair my mental state or the performance of my duties and compromise safety.
- Never discriminate on the basis of race, religion, color, creed, age, marital status, national origin, ancestry, gender, sexual preference, medical condition or handicap.
- Never harass, intimidate or threaten fellow members of the service or the public and stop or report the actions of other firefighters who engage in such behaviors.
- Responsibly use social networking, electronic communications, or other media technology opportunities in a manner that does not discredit, dishonor or embarrass my organization, the fire service and the public. I also understand that failure to resolve or report inappropriate use of this media equates to condoning this behavior.

**Developed by the National Society of Executive Fire Officers**

# A Student Guide to End-of-course Evaluations

## *Ten Things You Can Do to Improve the National Fire Academy*

The National Fire Academy takes its course evaluations very seriously. Your comments and suggestions enable us to improve your learning experience.

Unfortunately, we often get end-of-course comments like these that are vague and, therefore, not actionable. We know you are trying to keep your answers short, but the more specific you can be, the better we can respond.

| Actual quotes from student evaluations: | Examples of specific, actionable comments that would help us improve the course: |
|---|---|
| 1 "Update the materials." | • The (ABC) fire video is out-of-date because of the dangerous tactics it demonstrates. The available (XYZ) video shows current practices.<br>• The student manual references building codes that are 12 years old. |
| 2 "We want an advanced class in (fill in the blank)." | • We would like a class that enables us to calculate energy transfer rates resulting from exposure fires.<br>• We would like a class that provides one-on-one workplace harassment counseling practice exercises. |
| 3 "More activities." | • An activity where students can physically measure the area of sprinkler coverage would improve understanding of the concept.<br>• Not all students were able to fill all ICS positions in the exercises. Add more exercises so all students can participate. |
| 4 "A longer course." | • The class should be increased by one hour per day to enable all students to participate in exercises.<br>• The class should be increased by two days so that all group presentations can be peer evaluated and have written abstracts. |
| 5 "Readable plans." | • The plans should be enlarged to 11 by 17 and provided with an accurate scale.<br>• My plan set was blurry, which caused the dotted lines to be interpreted as solid lines. |
| 6 "Better student guide organization," "manual did not coincide with slides." | • The slide sequence in Unit 4 did not align with the content in the student manual from slides 4-16 through 4-21.<br>• The instructor added slides in Unit 4 that were not in my student manual. |
| 7 "Dry in spots." | • The instructor/activity should have used student group activities rather than lecture to explain Maslow's Hierarchy.<br>• Create a pre-course reading on symbiotic personal relationships rather than trying to lecture on them in class. |
| 8 "More visual aids." | • The text description of V-patterns did not provide three-dimensional views. More photographs or drawings would help me imagine the pattern.<br>• There was a video clip on NBC News (date) that summarized the topic very well. |
| 9 "Re-evaluate pre-course assignments." | • The pre-course assignments were not discussed or referenced in class. Either connect them to the course content or delete them.<br>• The pre-course assignments on ICS could be reduced to a one-page job aid rather than a 25-page reading. |
| 10 "A better understanding of NIMS." | • The instructor did not explain the connection between NIMS and ICS.<br>• The student manual needs an illustrated guide to NIMS. |

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# *UNIT 0: INTRODUCTION AND COURSE OVERVIEW*

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## WELCOME AND ADMINISTRATIVE MATTERS

- Class roster--Correct spelling of names, addresses, etc.
- Dining hall--K Building. Lunch break 12 noon until 1 p.m.
- Vehicle parking--Student vehicles must be parked in the lot adjacent to J Building.
- Breaks--At least one in the morning and one in the afternoon.
- Daily schedule--Classes begin at 8 a.m. and end at approximately 5 p.m.
- Phones and mail--Telephone in each dorm room and on the first floor of J Building. Mail can be picked up at the Security Office.
- Restrooms are located on each floor of J Building.
- Fire exits.
- No smoking.
- Student computer rooms.
- A class spokesperson will be chosen to attend the Superintendents' luncheon.
- Outside class activities.

## COURSE INTRODUCTION

### Course Topics

Unit 1: Fire in America.

Unit 2: Fire Dynamics and the Built Environment.

Unit 3: Fire-Related Human Behavior.

Unit 4: Egress Concepts.

Unit 5: Active and Passive Fire Protection Systems.

Unit 6: Hazardous Materials: Recognition and Control.

Unit 7: Fire Modeling Concepts.

## Other Requirements

In order to complete the course successfully:

- Attendance is required each day.
- Participation is expected during all activities.
- Students must achieve a score of at least 80 percent on the final examination.

## Activity 0.1

## Student Introductions

### Purpose

To introduce you to each other and to the instructors.

### Directions

1. Take a minute to complete these items.

   a. Name _____

   b. Title/Rank _____

   c. Department/Community character (urban, rural, industrial, residential, etc.) ____

   _____

   _____

   _____

   d. Your responsibilities or assignments _____

   _____

   _____

   _____

   e. Your experience with fire protection _____

   _____

   _____

   _____

f. Why you are taking this course _____

_____

_____

_____

g. Your expectations for this course _____

_____

_____

_____

2. This sheet will be collected by the instructors at the end of the activity.

# *UNIT 1:*
# *FIRE IN AMERICA*

### *OBJECTIVES*

*The students will be able to:*

1. *Compare factors that have, in the past, influenced attitudes toward fire and life safety in the United States.*

2. *Explain the attitudinal change required to reverse the history of fire loss in the United States.*

3. *Identify groups and organizations that are involved in, or can have an impact on, the many aspects of fire and life safety design in the United States.*

4. *Describe how risk to life and property from fire is an inherent element of all human activity and the human environment.*

5. *Recognize that risk considerations can change with changes in building use, occupant turnover, and property management practices.*

6. *Explain the roles codes and standards play in fire-safe building design.*

7. *Explain the difference between prescriptive and performance-based codes.*

8. *Explain the difference among codes, standards, recommended practices, and guides, and how they relate to the built environment.*

9. *Explain the general legal process for the adoption and enforcement of building and fire codes.*

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## INTRODUCTION

To be safe from fire in our homes and communities requires developing a partnership to ensure the safety of life and property among all the professionals who design and construct buildings, and the members of the fire community who oversee building design and completion. Working collaboratively, these professionals can resolve conflicts and speed the development process.

This unit will discuss the history of fire in the United States, attitudes about fire, and basic strategies to reduce fire occurrence and mitigate fire damage.

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# Activity 1.1

## Why Do We Care?

### Purpose

To open discussion on the purpose of protecting the built environment from fire and other hazards.

### Directions

1. You will work in your table groups.

2. Read the following question, and arrive at as many answers as possible and list them on an easel pad.

   Question: Why should the government at the local, State, or Federal level be interested in maintaining a fire-safe built environment?

3. Each table group should select a spokesperson who will present its comments and facilitate the discussion at the end of the activity.

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## THE UNITED STATES FIRE PROBLEM

The United States has a more severe fire problem than generally is perceived. Nationally, each year, there are millions of fires, thousands of deaths, tens of thousands of injuries, and billions of dollars lost--which makes the U.S. fire problem one of great national importance.

Although risk to life and property from fire is an inherent element of human activity and the human environment, the persistence of this serious fire problem also results from a failure to learn the lessons from past fire events. In many ways, the reason for this situation can be summarized by the comment of George Santayana that "those who do not learn from history are doomed to repeat it." By learning from our past and by working together in partnership, architects, engineers, code officials, and contractors can design and build a more fire-safe America.

### Statistics

The United States has had, and continues to have, one of the highest fire death rates in the industrialized world. In 1973, the year the Federal report *America Burning* was issued, an average of 12,000, people were killed each year in fires, and another 300,000 were injured. This means that in 1973 there were 56.6 fire deaths per million and 1,415 injuries per million.

Substantial progress has been made to decrease these numbers. In 2002, 3,380 civilians died in fires, and another 18,425 were injured (Karter, 2003, p. ii). While the population of the United States has increased approximately 37 percent from 1973 to 2001, the chance of being killed or injured in a fire has decreased dramatically.

**Nevertheless, while the death and injury rates have decreased each year, fire continues to kill more Americans than all natural disasters combined.**

**Number of Fires (Karter, 2003, p. i).**

- 1,687,500 fires were attended by public fire departments, a decrease of 2.7 percent from the year before.
- 519,000 fires occurred in structures, a very slight decrease of 0.5 percent.
- 401,000 fires or 77 percent of all structure fires occurred in residential properties.
- 329,500 fires occurred in vehicles, a decrease of 6.3 percent from the year before.
- 839,000 fires occurred in outside properties, a decrease of 2.6 percent.
- What do these fire frequencies mean? Every 19 seconds, a fire department responds to a fire somewhere in the Nation. A fire occurs in a structure at the rate of one every 61 seconds and, in particular, a residential fire occurs every 79 seconds. Fires occur in vehicles at the rate of 1 every 96 seconds, and there's a fire in an outside property every 38 seconds.

**Civilian Fire Deaths (Karter, 2003, p. ii)**

- 3,380 civilian fire deaths occurred in 2002, a decrease of 9.8 percent from a year ago, excluding the events of 9/11/01.
- About 79 percent of all fire deaths occurred in the home.
- 2,670 civilian fire deaths occurred in the home, a decrease of 14.1 percent, and the lowest figure since the National Fire Protection Association (NFPA) changed its survey methodology in 1977.
- Nationwide, there was a civilian fire death every 156 minutes.

**Civilian Fire Injuries (Karter, 2003, p. ii)**

- 18,425 civilian fire injuries occurred in 2002, a decrease of 9.2 percent. This estimate for civilian injuries is on the low side, due to under reporting of civilian injuries to the fire service.
- 14,050 of all civilian injuries occurred in residential properties, while 1,550 occurred in nonresidential structure fires.
- Nationwide, there was a civilian fire injury every 28 minutes.

**Property Damage (Karter, 2003, p. iii)**

- An estimated $10,337,000,000 in property damage occurred as a result of fire in 2002, a decrease of 2.2 percent from last year, excluding the events of 9/11/01.
- $8,742,000,000 of property damage occurred in structure fires.
- $6,055,000,000 of property loss occurred in residential properties.

While the tragic terrorism events of September 11, 2001, have drawn attention to various fire safety and fire protection issues, such events do not reflect the day-to-day occurrences in nearly every community in the United States. Most fire deaths and serious injuries occur one or two at a time, with larger events occurring on a more periodic basis.

## PAST STUDIES AND REPORTS

### President's Conference on Fire Prevention

The extent of the fire problem and mitigation methods has been studied for quite some time. The first formal study was conducted in 1947 by the President's Conference on Fire Prevention. President Harry S. Truman called for, hosted, and participated in this event. The participants in the conference were considered to be the most knowledgeable fire and construction safety experts in America at that time.

During the May 1947 conference, President Truman stated, "I can think of no more fitting memorial to those who died needlessly this year in the LaSalle Hotel fire in Chicago, the appalling disaster at the Winecoff Hotel in Atlanta, and the more recent New York tenement holocaust, than that we should dedicate ourselves anew to ceaseless war upon the fire menace."

President Truman also said, "The serious losses in life and property resulting annually from fires causes me deep concern. I am sure that such unnecessary waste can be reduced. The substantial progress made in the science of fire prevention and fire protection in this country during the past forty years convinces me that the means are available for limiting this unnecessary destruction."

### The Three "Es"

One of the results of the 1947 conference was the application of the Three "Es" to fire safety. While the United States military had used the Three Es in relation to safety considerations, the conference attendees formally applied the Three Es for the first time in the context of fire prevention. In this context, the Three Es are **Engineering**, **Education**, and **Enforcement**.

- **Engineering**. The conference recommended that fire safety design be incorporated into our Nation's engineering and architecture schools.

- **Education**. The basic purpose of prevention education is to change behaviors as they relate to fire safety and prevention. Fire departments historically have been involved in promoting the "Junior Fire Marshal" program, "Smokey Bear," home safety inspections, and other similar education programs. Nearly all American children can demonstrate "Stop, Drop, and Roll."

- **Enforcement**. Enforcement is probably the most unpopular method for achieving building or fire code compliance. Communities can achieve a higher level of fire prevention or safety when people are motivated to "do the right thing," and to correct hazardous conditions in a timely manner.

## 1947 Conference Findings

Fire safety in the built environment begins at the earliest design stages. The following is taken directly from the Report of the Committee on Building Construction, Operation and Protection contained in the 1947 President's Conference Report:

> It has been well said that fire safety begins in the designer's office. This observation may well be expanded to state that unless adequate fire safety is established there, it may never be fully obtained, since the cost of installing safety features, although relatively minor at the time of construction of the building, may be so prohibitive at a later date as to permit only partial compliance with generally accepted standards.
>
> Building practice is now so advanced a science that there is little excuse for erecting buildings that are deficient in any safety precautions. Structural design has progressed to the point where the safety of the building, from the strength standpoint, is taken for granted by the occupant. He has an equal right to assume that fire hazards in his building have either been eliminated or controlled.
>
> Nor should compliance with existing obsolete code requirements be offered as justification for failure to build up to modern standards. The competent designer is well acquainted with these standards, and safe construction should be his moral, if not legal, responsibility. The owner's responsibility to the occupants of his building should not permit the designer's advice to be disregarded. The records show quite clearly that the buildings in which the major losses of life by fire have occurred have fallen short, in one or more respects, of generally accepted standards.
>
> Stated simply, the basic principles of design of buildings for fire safety consist essentially of (1) the planning and construction of the building so as to minimize the chances of fire starting in the first instance, or of spreading beyond the point of origin; (2) the provision of sufficient and adequate exit ways, so that occupants can be quickly and safely evacuated if the need arises, (3) provision for the prompt discovery and reporting of fires and the necessary facilities for their extinguishments; and (4) attention to details that will minimize the hazards of smoke and noxious gases.

## *America Burning*

The fire problem in the United States was revisited in 1973 by the National Commission on Fire Prevention and Control. This Commission issued a report known as *America Burning*, which stated

> Few formal education programs anywhere in the United States for architects and engineers have course requirements in fire protection engineering. While some professional societies have committees concerning fire safety, few designers take an interest in the committee's work. For lack of training, many designers are unable to understand highly technical reports in fire safety design.
>
> This absence of training helps to explain the unenthusiastic attention that architects and engineers, when designing buildings, give to fire safety provisions. If the situation were turned around, that is, if architects and engineers were schooled in principles of fire safety, then undoubtedly they would participate enthusiastically in the search for alternative solutions and better codes consistent with the principles of fire safety.

The Commission made the following recommendations with regard to design professionals:

- Those schools giving degrees in architecture and engineering should include at least one course in fire safety.
- That the (proposed) National Fire Academy (NFA) develops short courses to educate practicing designers in the basics of fire safety design.
- That the Society of Fire Protection Engineers (SFPE) draft model courses for architects and engineers in the field of fire protection engineering.

This series of seminars is an attempt on behalf of the United States Fire Administration (USFA) to recognize the important role architects and engineers perform in fire-safe building design, and to enhance the working relationships between design professionals and code enforcement officials.

## The 1977 Report

In 1977, the National Fire Prevention and Control Administration (NFPCA), precursor to the USFA, published a report entitled *Learning from Fire: A Fire Protection Primer for Architects*. This report concluded, "The demand for safety lies behind the development of the understanding of fire, and ultimately forces the question:

> How much protection, and for whom…
>
> The issue of the level of protection has, in the past, been decided upon by fire professionals via life safety codes and building codes. It is clear that meeting minimum standards is often not only irresponsible, but simply not enough… Thus, the architect in understanding the dynamics of the fire phenomena is faced with the responsibility of explaining what levels of protection are possible for what price to his clients. Ultimately, the level of protection desired is a value question with political dimensions that must be put to and decided upon by the community…

> In the process of casting the built setting around human behavior, we have come to realize that this perspective opens exciting vistas for design innovation. The concepts of walls as barriers/bridges; rooms as compartments; furniture as fuel-packages; egress routes as life support systems; ceiling heights, window sizes and spacing as flame spread mechanisms all conjure design images that if dealt with creatively will, as much as our new energy consciousness, lead to exciting design solutions…. Innovations in design will probably demand re-thinking or re-interpretation of building codes, which in turn will demand institutional changes. This is the price we must pay for understanding.

## Lessons from September 11, 2001

There is no doubt that there are fire protection lessons to be learned from the terrorist events of September 11, 2001. Intensive research and analysis already has been conducted and more is under way by National Institute of Standards and Technology (NIST). More than likely, the research and analysis of these events only will support lessons we have already learned in the past. Damage to the structure's fire protection, lack of automatic fire suppression, ineffective or unclear communications, and an unusually severe fire contributed to the disaster. Our history teaches us that time and again the same factors are involved in large and tragic fire events. These are the events that happen on a regular basis in the United States in communities large and small.

**Fire loss categories.** Historical information shows that major fire losses fall into specific categories or situations that can be used to identify similar risks in any design situation.

- **places where people congregate**--theaters, drinking establishments, dance halls, schools, grandstands, arenas, factories, gambling halls, gymnasiums, etc.;
- **places where people sleep**--hotels, motels, dwellings, apartment houses, dormitories, lodges, etc.;
- **places where people are confined**--institutions, prisons, reformatories, etc.;
- **places where people are mentally or physically impaired**--institutions, hospitals, care facilities, nursing homes, homes for the aged, group care, day care centers, etc.;
- **places where hazardous materials are manufactured, processed, handled, or stored**--acids, chemicals, pesticides, explosives, flammable liquids, radioactive materials, etc.; and
- **buildings with large undivided areas**--department stores, grocery stores, warehouses, manufacturing plants, etc.

The list in Figure 1-1 shows some of the most famous and tragic fires that have occurred in the past 100 years, with the locations, dates, lives lost, and lessons learned and causes that often resulted in code changes.

| Fire | Date | Lives Lost | Lesson Learned/Code Changes |
|---|---|---|---|
| Iroquois Theater<br>Chicago, IL | 1903 | 602 | Egress door swing in places of assembly, combustible decorations, management of stage curtains, fire protection above stages. |
| Lakewood Grammar Sch.<br>Collinwood, CO | 1908 | 176 | Inadequate egress, lack of fire drills, bottleneck exits. |
| Triangle Shirtwaist Factory<br>New York, NY | 1911 | 145 | Locked exits, inadequate egress to fire escapes, combustible loads, and housekeeping. |
| Cleveland Clinic<br>Cleveland, OH | 1929 | 125 | Cellulose nitrate film storage practices. |
| Ohio State Penitentiary<br>Columbus, OH | 1930 | 320 | Inadequate egress supervision, lack of fire protection. |
| Rhythm Club<br>Natchez, MS | 1940 | 207 | Overcrowding, inadequate egress, combustible decorations. |
| Cocoanut Grove<br>Boston, MA | 1942 | 492 | Number of exits, egress door swing, interior finishes, overcrowding. |
| Barnum and Bailey Circus<br>Hartford, CT | 1944 | 168 | Combustibility of untreated fabric structures. |
| LaSalle Hotel<br>Chicago, IL | 1946 | 61 | Corridor door protection, enclosure of vertical openings. |
| Winecoff Hotel<br>Atlanta, GA | 1946 | 119 | Enclosure of vertical openings, inadequate egress, lack of early notification. |
| GM Transmission Plant<br>Livonia, MI | 1953 | 6 | Unprotected steel columns, combustible roof structure, and lack of fire protection. |
| Our Lady of the Angels Sch.<br>Chicago, IL | 1958 | 95 | Enclosure of vertical openings, prompt egress |
| Hartford Hospital<br>Hartford, CT | 1961 | 16 | Combustible ceiling tile and glue, delayed reporting, open doors onto corridors. |
| Golden Age Nursing Home<br>Fitchfield, OH | 1963 | 63 | Converted farmhouse with no fire separations or fire protection. |
| Marting Arms<br>Richmond, IN | 1968 | 41 | Gunpowder storage in sporting goods store. |
| Beverly Hills Super Club<br>Covington, KY | 1977 | 165 | Inadequate egress, lack of early notification, lack of fire protection and alerting systems. |
| MGM Grand Hotel<br>Las Vegas, NV | 1980 | 97 | Lack of sprinkler protection, floor-to-floor exterior fire spread, storage in corridors. |
| Great Adventure Amus. Pk.<br>Jackson Township, NJ | 1984 | 8 | Inadequate egress lighting, confusing exit paths, combustible finishes, lack of egress directions. |
| First Interstate Bank Bldg.<br>Los Angeles, CA | 1988 | 1 | Combustible load of office equipment, lack of sprinkler protection, maintenance of fire protection systems, presignal fire alarm. |
| Happy Land Social Club<br>Bronx, NY | 1990 | 87 | Inadequate egress, lack of fire protection. |
| One Meridian Plaza<br>Philadelphia, PA | 1991 | 3 | Lack of sprinkler protection, installation and testing of standpipe systems. |
| Imperial Foods<br>Hamlet, NC | 1991 | 25 | Locked exits, flammability of hydraulic oil, and lack of sprinkler protection. |
| Oakland Hills, CA | 1991 | 26 | Combustible vegetation, inadequate fire service access and water supply. |
| The Station<br>West Warwick, RI | 2003 | 100 | Interior finish, lack of automatic sprinkler protection, possible overcrowding. |

**Figure 1-1**
**List of Historic Fires and Causes**

## Why the High Loss Rate?

Risks to life and property from fire are inherent in human activity and in the natural environment, but why does the United States continue to have one of the highest fire death rates in the industrialized world? One substantial factor is "attitude." In the United States, our society's general outlook towards fire safety is influenced by such attitudes as:

- It doesn't happen to us/me.
- We have never experienced a fire.
- We are covered by insurance.
- It's just a fact of life.
- It's acceptable to have an accidental fire.
- The fire department will protect us/me.
- Fire protection is just too expensive.

Reducing current fire losses in the United States will require a change in these attitudes. All of us are challenged to rethink our approaches to life safety and fire protection.

In the 1985 report *Practices from Japan, Hong Kong, Australia, and New Zealand* (Schaenman & Seits, 1985), these differences in attitude are discussed at length. This report points out that, in Japan, the emphasis is on public awareness and individual responsibility for carefulness. In Hong Kong, fire prevention is stressed, but they also rely on built-in safety in highrise buildings where most Hong Kong residents live. For public education programs, they tap a different motivation than in Japan. In Hong Kong, people want to preserve their hard-won stake in life, however small.

## FIRE IMPACTS

The impact, or potential impact, of fire often is measured solely in monetary terms; that is, in the value of the building and its contents and the subsequent loss of jobs and tax revenue. While monetary concerns are real and must be considered, there are equally important organizational, legal, political, and psychological factors.

**Fire department**. One way a fire may affect the community is within the fire department itself. When an incident occurs resulting in a substantial structural loss, death, or serious injury, the fire department can be affected both directly and indirectly.

Since the fundamental goal of a fire department is to save lives and property, some individuals within the department may feel they have failed, or that the department is not up to standard. If

the fire department is not successful in its mission, it may have difficulty obtaining community support for funds and equipment. It may be held up to unfair and inflammatory scrutiny. When these feelings occur, personnel may leave, and recruiting new members also may become more difficult. An incident also may affect the department in terms of increased operating costs and lost or damaged equipment.

**Legal**. In today's litigious environment, any type of incident can generate civil litigation. A tenant may bring litigation against a design professional, building owner, or tenant for monetary loss, death, or injury. In the case of tenant-occupied properties, the building owner may pursue litigation if the tenant was in some way responsible for the cause or spread of the fire. An owner may bring litigation against the fire department if he/she believes that the department failed to take proper and appropriate actions in the area of fire prevention or suppression. Parties also may initiate litigation against the design professional for failure to ensure a fire-safe design.

Regardless of the underlying reason, litigation results in substantial out-of-pocket financial costs and time lost by both parties. While the fire may be over in a matter of hours, the subsequent litigation may continue for several years.

**Political**. A fire loss can have political effects. These can include loss of jobs, reduction in the tax base, loss of housing units, increases in insurance ratings/costs, and abandoned buildings. These conditions also can result in a deterioration of areas or neighborhoods, which in turn can provide a breeding ground for additional fire losses and crime. The political leaders of the community also may be faced with issues of providing temporary shelter and financial aid.

Political issues may affect the department as well as elected officials. People may see an official as a failure if the economy drops due to a fire. A fire may cause people to lose faith in their fire department and, in turn, in their city officials. The political impact may not show up until years later at an election.

**Physical/Psychological**. Nearly every fire has a psychological effect on the survivors. Survivors include property owners, tenants, burn victims, family and close friends of those injured or killed, department members, and the community at large.

A fire can inflict painful and serious damage on an individual. It can destroy body tissues to such a degree that basic life functions are impaired forever. An individual may be so disfigured that normal social or personal activities are impossible. Additionally, the experience of being engulfed in flames quite often leaves psychological scars so severe that the memory interferes with the person's ability to cope with everyday activities. The experience of being trapped in a fire and severely burned is so frightening that it produces anxiety, sleeplessness, and a constant reliving of the event for a considerable period of time.

Close family members and friends of the burn victim may struggle to meet the costs of ongoing medical treatments. Additionally, family may have trouble reconciling themselves to the disfigurement and coming to grips with the conflicting feelings of resentment, guilt, and compassion related to the injury or death.

Members of the responding fire department also may struggle with what they perceive to be their failure to prevent the death or injury.

The survivors may have to cope with the loss of their home, business, place of employment, and personal and family possessions. While insurance may be able to replace many of the physical items, some items are irreplaceable, and no amount of insurance can replace the sentimental or psychological connections to certain possessions.

## EFFECTS OF BUILDING DESIGN ON FIRE SAFETY

Community attitudes establish the community's overall level of acceptable fire risk. While the design professional cannot control these attitudes, building design professionals can influence fire and life safety in many ways.

- The design, installation, operation, and maintenance of buildings and their contents, including structural elements, insulation, interior finishes, furnishings, displays, decorations, and storage can minimize the adverse effects on building occupants, emergency responders, and the general public in the event of fire.

- Fire-safe building design can prevent incapacitation, death, chronic health effects, or lasting psychological or emotional harm caused by exposure to toxic or irritating fire effluents, or by distressing events resulting from exposure to fire.

- Design, management, and maintenance of buildings and premises to prevent physical damage to or dislocation of adjacent buildings and tenants within the same building can minimize the likelihood and extent of damage or disruption to the public infrastructure or rights of way in the event of a fire inside or outside a building.

- Fire-safe design, and fire-safe operation and maintenance of buildings and premises can prevent or control the likelihood of permanent or irreversible damage to the environment in the event of a fire involving a building element or building contents.

- Fire-safe design, operation, and maintenance of buildings and premises can prevent and/or control permanent or irreversible damage to the environment from the release of hazardous materials into the air, or of water onto land, from stocks stored, dispensed, processed, or used within the building or on the premises.

- The design, operation, management, and maintenance of buildings and premises to ensure fire safety mitigates the potential impact on the local or regional economy from unanticipated loss of employment, customers, and goodwill; reduction of tax base; and supply chain disruption.

- Designers can select fire safety features that minimize costs over the anticipated life of the building and still achieve the expected benefits in terms of loss of life, property, utility, and environmental quality.

## THE FIRE SAFETY CONCEPTS TREE

One tool that can be used by the design professional in the overall fire protection design is the Fire Safety Concepts Tree, contained in the National Fire Protection Association (NFPA) Standard 550, *Guide to the Fire Safety Concepts Tree*. The concept was originally developed in 1977 by several architects, and was contained in the 1977 report entitled *Learning from Fire: A Protection Primer for Architects.*

**Figure 1-2**
**Fire Safety Tree**

The Fire Safety Concepts Tree illustrates fire protection along three parallel lines: ignition prevention, fire development management, and protecting the exposed from fire's harmful consequences. As a design tool, the Fire Safety Concepts Tree can assist the design professional in analyzing the potential impact of a fire in a specific building and assist both the design professional and the code official in developing and analyzing means to deal with a fire event. Application of this concept can help identify deficiencies in the building's overall fire safety/fire protection plan.

The objectives of the Fire Safety Concepts Tree are defined or broken down as follows:

- **Preventing fire**. Selecting materials that are appropriate for the building's use, and separating combustible materials from potential ignition sources. This would include controlling ignition sources, controlling fuel properties, and maintaining separation of fuel and ignition sources.

- **Managing fire**. Ensuring continuous operations and performance of the building's functions should a fire occur. This includes support for firefighters, automatic suppression, fire control by construction, smoke control by construction, and regulating building contents.

- **Protection of exposed**. Safeguarding occupants and neighboring buildings, as well as their operations and contents. This would include fire-related occupant information, providing and identifying egress routes, refuge provisions, and accommodating the needs of special populations

## Risk Assessment Factors

Design professionals and code officials can use various factors to establish the design criteria of a building. These factors include occupancy classification; occupancy load; fire-related human behavior; risk factors associated with activities and operations; broader community value considerations; and possible conflicts among security, access, and egress. Risk considerations also can change with changes in these factors.

- **Occupancy classification**. In the prescriptive code approach, the basic foundation of code application is the determination of occupancy classification. Occupancy classifications reflect how a particular building will be used, including the characteristics of the occupants. For example, a restaurant is classified as a place of assembly. In this type of occupancy, people gather to enjoy food and beverages and may not be attuned to life safety issues. Therefore, the codes require extra fire safety features to protect people in unfamiliar surroundings.

- **Occupant load**. Occupant load factors are determined from the occupancy classification and reflect the "character" of the building or area. For example, the occupant load of a restaurant with table-and-chair seating area is calculated at one person per 15 net square feet, while an office building is calculated at one person per 100 gross square feet. Occupant load calculations establish the requirements for exiting: the higher the number of occupants, the more exiting is required.

- **Occupant behavior**. Many studies over the years have documented occupant behavior in order to understand the way occupants react to a fire or similar emergency situation. Based on this understanding, the codes establish requirements for the number and size of exits and their arrangement.

As an example, it is well-documented that occupants of a building will attempt to exit the building using the same path by which they entered. Therefore, codes require that the main exit in a place of assembly handle at least one-half of the total occupant load of the building.

Another example is a building, such as a hospital or nursing home, whose occupants may be incapable of self-preservation. In this type of building, the level of protection is increased by the use of compartmentalization and active fire protection systems (sprinklers and fire alarms).

- **Building use**. How a building is used also affects its overall fire safety. Buildings that house hazardous materials or processes present a higher level of danger to the occupants than buildings where those conditions do not exist. The level of fire risk often changes when a building is converted for different uses.

- **Building value or significance**. Buildings that have a special community value, or are of historical significance, may require or justify higher levels of fire protection to protect the integrity of the structure and its contents.

- **Security**. Since the terrorism events of September 11, 2001, concerns have grown about increased site and building security. These security concerns must be balanced carefully with the need for adequate fire department access to the site, and egress from the building by the occupants.

## Risk Mitigation Strategies

The risks related to fire and life safety can be mitigated by a variety of strategies. A single building may incorporate all or part of the following: control of fuel sources, control of ignition sources, operations and maintenance, detection and notification systems, fire suppression systems, management of smoke, thermal protection, structural integrity, compartmentalization, egress, manual fire department intervention, and rescue and recovery.

- **Fuel control**. Control of fuel sources encompasses a variety of aspects of building design and construction, beginning with the materials used for the construction of the structure itself, and ending with the building's contents/furnishings. As an example, the more combustible the building materials, the more stringent the requirements are for allowable area and height of the building. Thus, if the design professional is seeking a method for increasing the area and/or height of a particular building, this can be accomplished by choosing to use noncombustible materials in the structure.

- **Ignition source control**. Control of ignition sources is addressed in the safe design and installation of the various electrical, mechanical, and gas systems within the building.

- **Operations and maintenance.** While operations and maintenance are not controlled by the design professional, consideration should be given during the design stage to the actual operations and maintenance needs of the building and its systems.

  As an example, an automatic sprinkler system requires periodic disassembly for proper maintenance. If this sprinkler riser is located in a carpeted, finished office area, then it becomes extremely difficult to execute the required system maintenance. If, on the other hand, the riser is located in a mechanical room with a floor drain, then maintenance can be performed much more effectively.

- **Detection and notification systems**. Detection and notification systems are manual and automatic fire alarm and detection systems. When these systems are properly designed, installed and maintained, they can provide many important fire safety functions, such as early detection of hostile fire; notification of the building occupants; notification of emergency forces; and control of other building systems, such as smoke control, fire doors, and elevators.

- **Fire suppression**. The most common type of fire suppression system is the automatic fire sprinkler system. Sprinkler systems have an enviable record of protecting lives and property where they are installed.

  While originally intended for property protection, a properly designed, installed, and maintained automatic sprinkler system greatly increases the level of life safety in any building.

  Use of such protection also has other benefits, since many of the codes have built-in equivalencies when such protection is provided. For example, a designer may increase the area and height of a structure when it is outfitted with a complete fire sprinkler system.

- **Smoke management**. A structural fire can produce large quantities of extremely toxic smoke and fire gases. Even when automatic sprinkler protection is provided, a certain amount of smoke and fire gases will be produced. Smoke and fire gases can be controlled by the use of various mechanical means, such as pressurization and/or exhaust. Proper smoke control and management decreases property damage and increases the level of life safety for the occupants.

- **Thermal protection**. Thermal protection, structural integrity, and compartmentalization are features that often work together in a structure. Thermal protection is simply a coating or membrane applied to a structural member to provide a specified degree of fire resistance and structural integrity under hostile fire conditions.

- **Compartmentalization**. Compartmentalization is the dividing of a building into separate areas by fire-rated construction, to limit the spread of fire, smoke, and fire gases.

- **Egress**. Proper egress from a building involves capacity, location, arrangement, and configuration to reflect the number and characteristics of the occupants and the occupancy.

- **Access**. While the building codes anticipate a fire department response for manual fire-fighting, rescue, and recovery in the event of a fire or similar event, the level of response can vary greatly from one jurisdiction to another. Relying heavily upon the response of the fire department to mitigate the dangers to the occupants in the event of a structural fire can lead to disaster. The response of the fire department cannot overcome a lack of proper egress, presence of improper interior finishes, lack of sufficient early warning, or automatic fire suppression.

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# Activity 1.2

## Influencing Fire Safety Objectives

### Purpose

To employ the Fire Safety Concepts Tree to satisfy fire protection objectives.

### Directions

1. You will work with your table groups.

2. Each table group will use the fire protection examples below and the Fire Safety Concepts Tree on the following page.

3. Using the Fire Safety Concepts Tree, you are to describe the path through the Tree that explains that example.

4. Each table group should select a spokesperson who will present its comments and facilitate the discussion at the end of the activity.

### Examples

1. A dry sprinkler is installed in the soffit above the exterior deck of an apartment to protect it from a barbecue fire.

2. An architect designs a hospital site plan so the entire exterior wall of the intensive care unit (ICU) is at least 100 feet from the adjacent property's outdoor flammable liquid storage.

3. The industrial painting operation includes explosion-proof electrical fixtures in the paint room.

4. An automatic sprinkler system is installed as part of a remodel of an historic building.

5. Exterior fire escape stairs are enclosed by a 1-hour fire-resistance-rated shaft.

6. A 480,000 British thermal unit (Btu)-per-hour input boiler is installed in a 2-hour fire-resistance-rated room.

7. The glass surface in the exterior wall of a building erected on a property line is reduced from 8,000 square feet to 2,000 square feet.

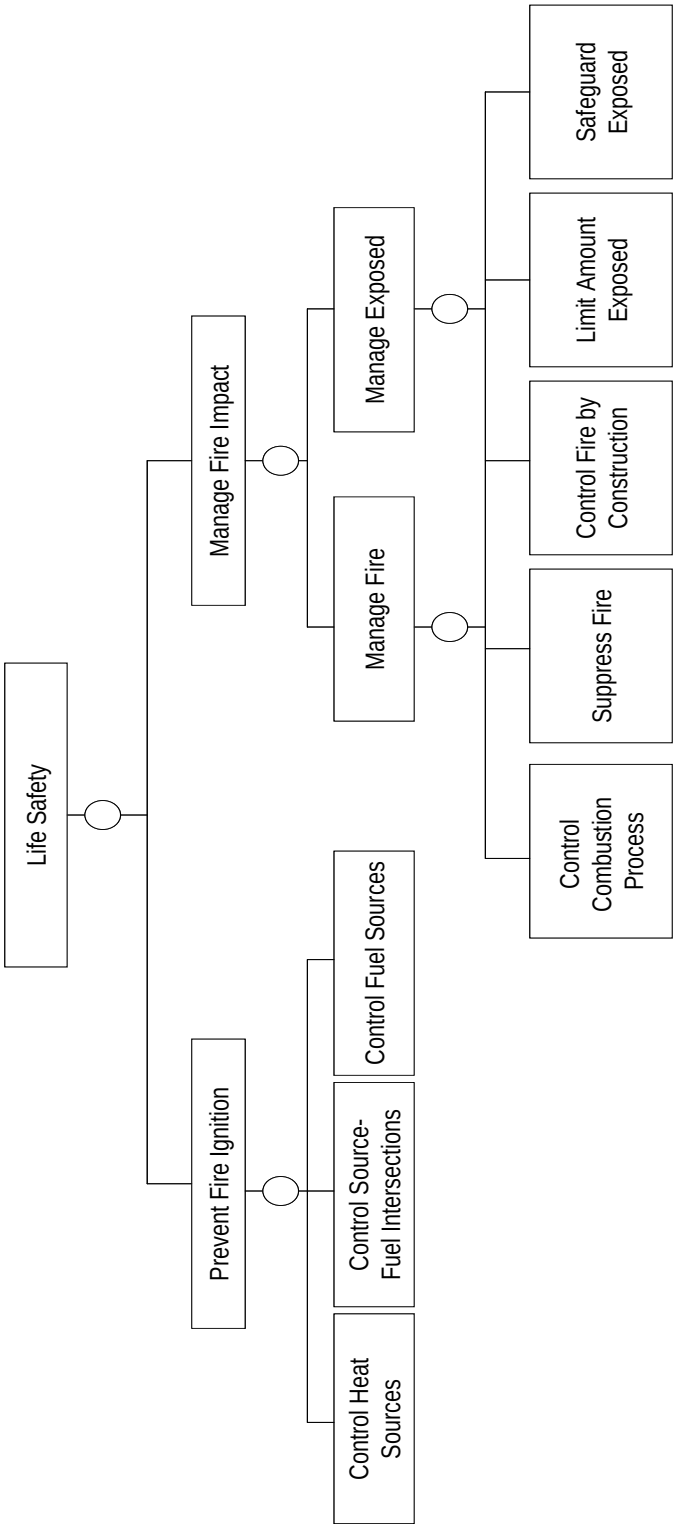
8. A 100,000-cubic-foot pile of tires stored outdoors is reduced to 50,000-cubic-feet.

9. The fuel gas line supplying natural gas to the ranges in a commercial kitchen is equipped with an automatic shutoff device.

10. The fire marshal issues an outdoor burning ban due to extremely dry conditions.

## Activity 1.2 (cont'd)

## Fire Safety Concepts Tree



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## BUILDING AND FIRE CODES

There is a wide variation in the history of building and fire codes in each State. In some cases, local government fire safety ordinances predate State codes because the cities existed before statehood. State governments usually have fire safety statutes that predate the adoption of one of the model fire codes. Although some States have replaced all of their disparate statutes with a model fire code and have preempted any local fire safety ordinances that preceded statehood, others melded the two by keeping some of the statutes and deleting conflicting requirements in the model code. There may be no readily discernible logic as to how a State addressed this situation, because each State has had a unique political history.

Fire safety and building regulations at the State and local levels have tended to develop in a piecemeal fashion because fire safety issues were dealt with as they evolved. For example, disastrous theater fires such as the 1903 Iroquois Theater in Chicago (one of the 10 deadliest fires of all time) raised the fire safety issues of smoking and overcrowding in theaters. Shortly after that fire, several States adopted regulations to prohibit smoking and limit the number of occupants in theaters. As each State government identified a specific fire safety issue, the State legislature would draft a statute that dealt with that specific issue.

The piecemeal approach to fire safety and building regulations began changing in the early 1900s. A number of property insurance organizations formed a group to distribute a collection of fire safety requirements that applied to the typical situations found in most jurisdictions. The organization originally was called the National Board of Fire Underwriters (NBFU) and later changed its name to the American Insurance Association (AIA). It called its compilation of fire safety guidelines a "model fire code," and recommended that State and local governments adopt it to replace the unsystematic collection of laws and ordinances that was being used. The AIA fire code ceased publication in 1976.

### The Legacy Code Groups

Since the 1950s, there have been three model building code organizations in the United States publishing their own building and fire codes. A model code group is one that publishes both a building and fire code. It may also publish related construction codes such as mechanical and plumbing codes. The three predominant model fire codes were the *BOCA/National Fire Code* from BOCA (Building Officials & Code Administrators International, Inc.), the *Uniform Fire Code* from ICBO (International Conference of Building Officials), and the *Standard Fire Code* from SBCCI (Southern Building Code Congress International, Inc.).

The *Uniform Fire Code* originally was a cooperative venture between the Western Division of the International Association of Fire Chiefs (IAFC) and ICBO. The Western Fire Chiefs Association (WFCA) created and maintained the code, and ICBO handled the publishing. In 1991, the two organizations formed a new organization, which is now responsible for the *Uniform Fire Cod*e, the International Fire Code Institute (IFCI). At about the same time, the SBCCI agreed with the Southeastern and Southwestern Divisions of the IAFC to have those organizations maintain the *Standard Fire Code*.

The model fire codes offered two advantages that the AIA fire code did not have. First, the fire codes cross-referenced related material in their companion building codes. Second, the model codes were **consensus** documents, that is, they were debated and approved by the membership of building and fire officials, which gave those codes a wide base of support.

## The International Code Council

In 1994, the three model code groups (BOCA, ICBO, and SBCCI) founded the International Code Council (ICC) as a nonprofit organization dedicated to developing a single set of comprehensive and coordinated national model construction codes. The ICC has developed and published an impressive inventory of international codes, including:

- *International Building Code*;
- *Performance Code for Buildings and Facilities*;
- *International Energy Conservation Code*;
- *International Fire Code*;
- *International Fuel Gas Code*;
- *International Mechanical Code*;
- *International Plumbing Code*;
- *International Private Sewage Disposal Code*;
- *International Property Maintenance Code*;
- *International Residential Code*;
- *International Zoning Code*; and
- *ICC Electrical Code Administrative Code*.

Beginning in 2000, the three model code groups ceased publishing their own individual documents. However, many local and State jurisdictions continue to use documents from the three prior code groups. ICC has committed continuing support for what they call the "legacy" codes until they are replaced at the State and local level by the "I-Codes."

## National Fire Protection Association

The NFPA has published, since the 1880s, various documents dealing with fire and building safety. Until recently, the NFPA has not published a building code; however, it published the *Life Safety Code*® also known as NFPA 101®. This document originated in 1913 along with several reports that included "Outside Stairs for Fire Exits," "Safeguarding Factory Workers from Fire," and "Exit Drills in Factories, Schools, Department Stores and Theatres." These reports led to the first edition of the *Building Exits Code* published in 1927. The *Building Exits Code*, became the *Life Safety Code*® in 1966.

In addition to the *Life Safety Code*®, NFPA has since 1975 published NFPA 1, *Fire Prevention Code*. This code correlates with the NFPA's numerous fire safety standards. In 2003, the title of this document changed to NFPA 1, *Uniform Fire Code*™. As part of the Comprehensive Consensus Codes (C3) set effort, NFPA and WFCA have integrated NFPA 1, *Fire Prevention Code* and the *Uniform Fire Code*™ (UFC).

In July 2002, NFPA issued the first edition of NFPA 5000, *Building Construction and Safety Code*®. NFPA 5000® contains provisions for every aspect of the design and construction of buildings and structures, as well as the design of integrated building systems for health, safety, comfort, and convenience. It provides for the selection and design of building construction types and structural design systems and assemblies, as well as fire protection systems and egress design requirements for life safety and protection. It is also the only building code featuring an occupancy-based format, along with integrated provisions for both performance-based design options and the rehabilitative use of existing buildings.

NFPA 5000® will be a cornerstone of the first full, integrated set of American National Standards Institute (ANSI)-accredited codes and standards. The C3 set is being developed through a partnership involving NFPA, the International Association of Plumbing and Mechanical Officials (IAPMO), WFCA, and the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE). The C3 set will offer coordinated and integrated safety codes for the entire building community, including:

- NFPA 5000®;
- NFPA 70, *National Electrical Code*®;
- NFPA 101®;
- NFPA 1;
- NFPA 54, *National Fuel Gas Code*;
- NFPA 58, *Liquefied Petroleum Gas Code*;
- NFPA 30, *Flammable and Combustible Liquids Code*;
- NFPA 30A, *Code for Motor Fuel Dispensing Facilities and Repair Garages*;
- *Uniform Mechanical Code*;
- *Uniform Plumbing Code*; and
- NFPA 900, *Building Energy Code* (ASHRAE 90.1 and 90.2).

## Occupational Safety and Health Administration

The U.S. Occupational Safety and Health Administration (OSHA) has revised its standards for means of egress, concluding that NFPA's 2000 edition of the *Life Safety Code*® provides comparable safety to OSHA's Exit Routes Standard. The OSHA final rule, which became effective December 7, 2002, permits employers to comply with NFPA 101® (2000) to meet means of egress standards for workplace safety.

## Americans with Disabilities Act

The Americans with Disabilities Act (ADA) was passed July 26, 1990, as Public Law 101-336 (42 U.S.C. Sec. 12101 *et seq*.) and became effective on January 26, 1992. The ADA is landmark Federal legislation that opens up services and employment opportunities to the 43 million Americans with disabilities. The law was written to strike a balance between the reasonable accommodation of citizens' needs and the capacity of private and public entities to respond. It is not an affirmative action law but is intended to eliminate illegal discrimination and level the playing field for disabled individuals.

The law is comprised of five titles that prohibit discrimination against disabled persons within the United States. Titles I and II are the primary sections that affect local governments.

Title I prohibits employers, including cities and towns, from discriminating against qualified job applicants and workers who are or who become disabled. The law covers all aspects of employment including the application process and hiring, training, compensation, advancement, and any other employment term, condition, or privilege.

Title II prohibits State and local governments from discriminating against disabled persons in their programs and activities. Title II also sets forth the applicable structural accessibility requirements for public entities.

Title III prohibits private enterprises that provide public accommodations and services (e.g., hotels, restaurants, and transit systems) from denying goods, services, and programs to people based on their disabilities. Title III also sets forth the applicable structural accessibility requirements for private entities.

Title IV makes available telecommunications devices and services for the hearing and speech impaired. These regulations spell out certain mandatory minimum standards telephone companies must maintain to be in compliance with the ADA.

Title V includes some miscellaneous provisions that relate to the construction and application of the ADA, including alternative dispute resolution.

Under the provisions of the ADA, the Federal government has promulgated the Americans with Disabilities Accessibility Guidelines also known as ADAAG. This document contains scoping and technical requirements for accessibility to buildings and facilities by individuals with disabilities under the ADA of 1990. These scoping and technical requirements are to be applied during the design, construction, and alteration of buildings and facilities covered by Titles II and III of the ADA to the extent required by regulations issued by Federal agencies, including the Department of Justice and the Department of Transportation, under the ADA.

The provisions of the ADAAG are very similar to those contained in ANSI A117.1-1980.

## Other Groups and Organizations

### Underwriters Laboratories

Underwriters Laboratories, Inc, common known as UL is an independent, not-for-profit product certification organization that has been testing products and writing standards for safety for since 1894. UL evaluates more than 19,000 types of products, components, materials, and systems annually.

### American National Standards Institute

ANSI coordinates the development and use of voluntary consensus standards in the United States and represents the needs and views of U.S. stakeholders in standardization forums around the globe. ANSI was founded in 1918. The Institute oversees the creation, promulgation, and use of thousands of norms and guidelines that directly affect businesses in nearly every sector: from acoustical devices to construction equipment, from dairy and livestock production to energy distribution, and many more. ANSI also is engaged actively in accrediting programs that assess conformance to standards--including globally recognized cross-sector programs such as the ISO 9000 (quality) and ISO 14000 (environmental) management systems.

### American Society for Testing and Materials

ASTM International is one of the largest voluntary standards development organizations in the world--a trusted source for technical standards for materials, products, systems, and services. Known for their high technical quality and market relevancy, ASTM International standards have an important role in the information infrastructure that guides design, manufacturing, and trade in the global economy.

ASTM International, originally known as the American Society for Testing and Materials (ASTM), was formed over a century ago, when a forward-thinking group of engineers and scientists got together to address frequent rail breaks in the burgeoning railroad industry. Their work led to standardization of the steel used in rail construction, ultimately improving railroad safety for the public. As the century progressed and new industrial, governmental, and environmental developments created new standardization requirements, ASTM answered the call with consensus standards that have made products and services safer, better, and more cost-effective. The proud tradition and forward vision that started in 1898 is still the hallmark of ASTM International.

Today, ASTM continues to play a leadership role in addressing the standardization needs of the global marketplace. Known for its best-in-class practices for standards development and delivery, ASTM is at the forefront in the use of innovative technology to help its members do standards development work, while also increasing the accessibility of ASTM International standards to the world.

ASTM continues to be the standards forum of choice of a diverse range of industries that come together under the ASTM umbrella to solve standardization challenges. In recent years, stakeholders involved in issues ranging from safety in recreational aviation, to fiber optic cable installations in underground utilities, to homeland security, have come together under ASTM to set consensus standards for their industries.

Standards developed at ASTM are the work of over 30,000 ASTM members. These technical experts represent producers, users, consumers, government, and academia from over 100 countries. Participation in ASTM International is open to all with a material interest, anywhere in the world.

## Other Commonly Referenced Publications

### *Fire Protection Handbook*

This publication of the NFPA has been referred to often as the "bible of fire protection." Others refer to it as the "reference of record." The "handbook" was first published in 1896. The first editions were known as *Handbook of the Underwriter's Bureau of New England.* The first seven editions were authored and published by Everette Crosby, Henry Fiske, and H. Walter Forster. In 1935, these individuals donated all rights to the handbook to NFPA. Beginning in 1935 with the eighth edition, the handbook was compiled and published by the NFPA. The original authors continued to cooperate in an advisory capacity on subsequent editions until their deaths, and some of their statements on fundamentals remain unchanged.

The handbook continues to be updated on a periodic basis.

A complete history of the handbook can be found in Appendix C of the 19th edition of the handbook entitled "What Time has Crystallized into Good Practice: The Fire Protection Handbook from 1896 to 2003"

### The *Handbook of Fire Protection Engineering*

This publication of the SFPE since its inception is a contribution toward documenting and integrating the theoretical and applied bases of fire protection engineering. The handbook strives to provide a more useful and direct link from the fundamental chapters to actual use in practice.

The handbook contains chapters on fundamentals, fire dynamics, hazard calculations, design calculations, and fire risk analysis

Like the NFPA *Fire Protection Handbook*, the SFPE *Handbook* is updated on a periodic basis.

## ADOPTION OF CODES AND STANDARDS

The building and fire codes do not have the force of law until they are formally adopted by a law or regulation that gives them that authority. State governments have two options for making a model fire code legally enforceable. The legislature can enact a statute saying so, or it can authorize a State agency to enact a regulation that says the same thing. Even if not legally adopted, codes and standards may be considered the professional standard of care to be followed.

A **statute** is a law that is enacted by a legislature. A **regulation** is a governmental order written by a governmental agency at the direction of the legislature, and it has the force of law. The legislature gives a regulation the force of law by stating so in the same statute that authorizes the State agency to create a regulation.

Governments have two methods of adopting a building and fire codes. The first is **transcription**, where the government enacts a regulation that literally copies the entire code into the regulation and places the jurisdiction's title on it in place of the code title.

The other method is to adopt the model code by **reference**. With the reference method, the jurisdiction adopts a short regulation stating that the code in question is legally enforceable as the jurisdiction's fire safety regulations.

Jurisdictions using the transcription method must print copies of the code for people to use. The reference method is more popular because the codebooks are available from the code organizations. The reference method will be discussed in a later section of this unit.

Another reason for the popularity of the reference method of adoption is its efficiency. Some States add amendments to the codes, for example the deletion of a specific chapter or the addition of more stringent requirements. But for the most part the building and fire codes provide a complete set of building and fire safety requirements that will apply to situations found in every jurisdiction.

The codes have two other distinct advantages. They have a broad base of support, i.e., dozens of States, and the large number of adopting jurisdictions increases the confidence that the codes in question are reasonable. In addition, the ICC and the NFPA regularly publish revised editions; this provides for regular improvements to existing requirements as well as the timely adoption of requirements that apply to new materials or processes. If each State were to create its own agency to perform this regular updating and introduction of new topics, it would create a great deal of redundant actions that would not have the broader base of support afforded by the codes.

The code development process is intended to be one in which all interested persons can participate. The code groups use a "consensus" process: that is, any person or organization can propose changes to the building and fire codes and standards. Architects, engineers, product developers, citizen activists, fire, or building officials may submit changes, support them in public hearings, and shepherd them through the approval process.

The consensus development process is intended to ensure that all interests are equally and well served, thereby preventing one interest group from controlling the process. While the two predominant code development groups, the ICC and NFPA, have slightly different code development processes, architects and engineers are encouraged to get involved to represent their clients.

Although code adoption by reference is the most frequently used of the two options noted, States still may have additional statutes or regulations regarding fire safety. The statutes might address an issue that is peculiar to the State and not adequately dealt with in the model code. Or, a statute might enact more stringent measures on a specific fire safety issue than are found in the model codes. Two examples are sprinkler requirements and the definition of a highrise building.

Many States have enacted statutes or regulations that require sprinklers in certain occupancies that are not required in the model codes. Some of these sprinkler requirements are retroactive, where the model code requirements are not unilaterally retroactive. Also, some States have amended the definition of highrise buildings in the model codes by lowering the building heights that define highrise buildings, thus applying their model code's highrise fire protection requirements to more buildings.

For example, the State of Michigan defines a highrise building as one greater than 40 feet in height. Thus, a building taller than 40 feet would require the same fire protection features that are called for in the two model codes used in Michigan, even though one of the model codes uses 75 feet to define highrises and the other uses 55 feet.

## Mini-Max Codes

States that adopt a statewide fire code do not necessarily make it the exclusive fire code for their local governments. Where this is the case, local governments can elect to use the State fire code or enact their own. However, some States add a provision to their adopting language that prohibits local governments from adopting fire codes that are less stringent than the State code. In States where this is the case, the State fire code is called a **mini** code.

A number of States go further than the **mini** limitation and add a **maxi** limitation as well. This limitation can take two forms. The limitation may state that local fire codes cannot be more restrictive, or the language provision can state that local jurisdictions cannot adopt regulations that **differ** from the State code. Both forms of the limitation will make the State code effectively both the minimum and maximum building and fire safety requirements, since another building or fire code could only be different by containing requirements that were less restrictive or more restrictive than the State fire code. Where this type of limiting provision is used, the code is called a **mini-maxi** code.

Local automatic fire sprinkler requirements are an example of these limitations. If the State mini-maxi code says that sprinklers are not required in retail occupancies unless the occupancy is larger than 12,000 square feet, a local jurisdiction could not enact an ordinance that requires sprinklers in smaller, like occupancies. This ordinance would be more stringent than the State

code, and therefore would be illegal. The same goes for an ordinance that might be less restrictive than a State code requirement.

Mini-maxi codes are controversial in the fire service. While they afford the development and construction industry relatively predictable and consistent rules and regulations from community to community, mini-maxi codes prevent fire officials from adopting laws that may pertain to their specific circumstances. For example, a seasonal resort community on a large body of water may be faced with providing fire protection for scores of valuable yachts moored in combustible boathouses extending hundreds of yards from the shore. A mini-maxi code would prevent the fire official from adopting regulations requiring built-in fire protection for this expensive and challenging risk.

## Codes, Standards, Recommended Practices, and Guides

**Codes** are mandatory provisions using the word **shall** to indicate requirements. Codes are written in a form generally suitable for direct adoption into law. They set forth minimum requirements to protect the health and safety of society and generally represent a compromise between optimum safety and economic feasibility. Codes are written in legally adapted language and are intended to be adopted by the appropriate legislative body into the local or State statutes. There are two types of codes:

- Specification--These spell out in detail what materials can be used, the size of components, and how they are to be assembled. These also may be called "prescriptive" codes.

- Performance--These detail the objective to be met and establish criteria for determining whether the objective has been met.

Alternate methods and materials can be selected as long as it can be shown that the performance criteria can be met. Performance-oriented codes still embody a fair amount of specification-type requirements, but the provision exists for substitution of alternate methods and materials if they can be proven adequate "tradeoffs."

Requirements found in codes are excerpts from, or based on, the standards published by nationally recognized organizations. In other words, the code mandates that something **must** be done, and the standard specifies **how** it is to be done.

**Standards** also contain mandatory provisions using the word **shall** to indicate requirements. The most extensive use of standards is their adoption into the code by reference, thus keeping the code to a workable size and eliminating duplication of effort. Examples of such standards are those that deal with:

- design, installation, and testing of extinguishing systems;
- storage and handling requirements for flammable liquids;
- safety procedures for hazardous processes;

- definition and identification of combustible dusts;
- selection and installation of building materials;
- design, installation, and testing of fire protection water systems; and
- design, installation, and testing of mechanical systems.

**Recommended practices** are advisory provisions only, using the word **should** in the text. **Should** means that the contents are advised, but not required. They are published by nationally recognized organizations, and are intended to deal with maintenance and operational standards for the various systems required by the code. Recommended practices can be adopted into the code by reference, and usually are used by the code official as guides to determine compliance with the intent of the code writers.

**Guides** are advisory in nature and may give instructions, but do not contain mandatory provisions. They are written by nationally recognized organizations. Guides are intended to explain the codes' and standards' written intent. Guides provide methods to the code official or testing agencies to assess the degree to which the system has met the intent of the standard. Guides are not adopted by reference, but can be included in a standard. Guides can be considered to be a "standard of care."

# Activity 1.3

## Evaluation of History and Progress

### Purpose

To compare progress made on fire issues.

### Directions

1. View the PBS video "Why America Burns."

2. At the end of the video, groups should compare and contrast the fire issues discussed in the video with the current conditions.

3. Individuals will report on what changes have occurred in their own department/ community over the same time period with regard to the fire problem.

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## INTRODUCTION TO PERFORMANCE-BASED DESIGN AND CODES

The traditional approach used in the building and fire codes in the United States has been that of specification or prescriptive-based codes. Prescriptive-based codes establish requirements based on the broad or generic classifications of buildings or occupancies. Such requirements are stated typically in terms of fixed values such as travel distance, fire-resistance ratings, allowable area and height, number of plumbing fixtures, number and capacity of exits, fire alarm and detection systems, and fire suppression systems.

By definition, performance-based design is an engineering approach to design elements of a building based on performance goals and objectives, engineering analysis, and quantitative assessment of alternatives against the design goals and objectives, using accepted engineering tools, methodologies, and performance criteria.

Performance-based codes are not based on broad or generic classifications, but establish acceptable or tolerable levels of hazard or risk for a variety of health, safety, and public welfare issues. As part of the development of the new family of "International Codes," the ICC has developed the *Performance Code for Buildings and Facilities*. Beginning with the 2000 edition, NFPA 101® contains Chapter 5 entitled "Performance-Based Design." The provisions of NFPA 5000® also contain a performance-based design option.

While having extensive or detailed requirements for "performance" is relatively new to the building and fire codes used in the United States, the concept is not. The *BOCA National Building Code*, *Standard Building Code*, *Uniform Building Code*, *International Building Code*, and NFPA 101® all have contained provisions for "alternative methods and materials" or "equivalencies." These code provisions allow for the use of alternative equipment or materials not specified or prescribed in the code, if the authority having jurisdiction (code official) approves it. The provisions also permit the code official to approve the alternative or equivalency if it is shown to be equivalent in quality, strength, effectiveness, fire resistance, durability, and safety. The proponent of the alternative method or equivalency is responsible for providing all necessary documentation to the code official.

There has been, and continues to be, a strong movement in the United States to move our building and fire codes toward the performance-based concept. This movement began even before the development of the international codes. At least a part of the justification for this movement is the use of such codes by other countries. However, although performance-based codes have been used successfully in other countries such as New Zealand, it is important to consider all of the variables or differences between these countries and the United States.

### The Performance-Based Approach

Performance-based codes address a building's unique aspects or uses, specific "stakeholder" needs, and, in some instances, the broader community's needs. This approach provides that the development and selection of alternative fire protection options be based on the needs of the specific project, rather than the broad occupancy classification. Performance-based design results

in a fire protection and life safety strategy in which fire protection and building systems are integrated, rather than designed in isolation.

The performance approach allows for comparison of safety levels provided by various alternative designs. Performance-based design also provides a mechanism for determining what level of safety is acceptable to the stakeholders and at what cost. Performance-based codes require the use of a variety of tools for proper analysis. Such tools might include deterministic analysis techniques, probabilistic analysis techniques, application of the theory of fire dynamics, application of deterministic and probabilistic fire effects modeling, and application of human behavior and toxic effects modeling.

**Probabilistic analysis** and models deal with the statistical likelihood of the occurrence of a fire and its outcome based on the random nature of fire and the likelihood of occurrence. **Deterministic analysis** and models are based on specific physical conditions and use calculations that are based on physical laws or correlations developed as a result of fire test data to predict fire outcomes.

## Stakeholders

The performance-based design concept involves a wide range of "stakeholders." Stakeholders include all individuals or their representatives who have an interest in the successful completion of the specific project. Clearly, stakeholders include not only the members of the design team, the building owner, and developer, but the code enforcement officials as well. The design team is a group of stakeholders that includes individuals such as representatives of the architect, building owner, developer, and any other pertinent engineers and designers.

## Purpose of Performance-Based Codes

The overall purpose of a performance-based code is to provide appropriate health, safety, welfare, social, and economic value, while promoting innovative, flexible, and responsive solutions, which optimize the expenditure and consumption of resources. The code intends buildings to provide for:

- an environment free of unreasonable risk of death and injury from fires;
- a structure that will withstand loads associated with normal use and of the severity associated with the location in which the structure is constructed;
- means of egress and access for normal and emergency circumstances;
- limited spread of fire both within the building and to adjacent properties;
- ventilation and sanitation facilities to maintain the health of occupants;
- natural light, heating, cooking, and other amenities necessary for the well-being of the occupants; and
- efficient use of energy.

## Building Owner's Responsibility

The owner of the building is responsible for retaining and furnishing the services of qualified design professionals and the costs of any special services, including contract or third-party reviews required by the code official. The building owner also must retain all required documents and reports on the premises and is required to operate the building in accordance with the approved design.

## Design Professional's Responsibility

The design professional is registered or licensed to practice as defined by the statutory requirements of the professional registration laws of the State or jurisdiction in which the project is to be constructed. The design professional must possess the required knowledge and skills to perform design, analysis, and verification in accordance with the code requirements and applicable standards of practice. Design professionals and special experts must be able to apply performance requirements; provide appropriate analysis, research, computations, and documentation; use authoritative documents and design guides; and review the completed construction elements to verify compliance with the prescribed design.

All design documentation must be prepared by the design professional. Required documentation includes a concept report, design report, and an operations and maintenance manual. The design professional must coordinate all plans and documents for consistency, compatibility, and completeness, and submit them to the code official for review and approval.

## Code Official's Responsibility

The code official is required to perform a "knowledgeable" review of the proposed design and is permitted to use a third party or peer review. When such third party or peer review is used, the cost for such services may be passed on to the submitter. Once the plans and specification have been reviewed and approved, a permit is issued for the start of construction. During the construction process, inspections and tests must be conducted in accordance with the design documents, code official procedures, and applicable codes. Upon completion, acceptance testing must be undertaken prior to occupancy.

## Acceptance Testing

Upon completion of the project and acceptance testing, the design professional must prepare and submit to the code official documentation that verifies that all performance and prescriptive code provisions have been met. The code official is permitted to require a third party or peer review of this documentation. Upon completion of construction, final inspection and testing, and submission of all required documentation, the code official must issue the certificate of occupancy. A temporary certificate of occupancy may be issued for a limited timeframe with specified conditions, provided all life safety items are accepted.

## Operations and Maintenance Manual

The owner is responsible for proper maintenance and operation throughout the life of the building in accordance with the "Operations and Maintenance Manual." The building owner also is responsible for periodically verifying compliance with the approved design at a frequency approved by the code official. Documents verifying that the building, facilities, premises, processes, and contents are in compliance with the approved design documents must be filed with the code official.

## Renovations, Alterations, Change of Occupancy

When a building that was designed and constructed using a performance-based design is remodeled or altered, or its use changes, a design professional must evaluate the existing building and applicable documentation. Any change that results in an increase in hazard or risk must undergo a full evaluation of design. The review and evaluation must be documented in a written report and submitted to the code official for review and approval. Such written review must be submitted to the code official even when the proposed changes do not exceed the original conditions.

## Summary of Performance-Based Codes and Design

The use of performance-based codes and performance-based design clearly offers an alterative approach to achieving appropriate level of fire and life safety during design, construction, and occupancy. However, it is expected that the majority of buildings will continue to be designed and constructed using the traditional prescriptive code approaches.

## SUMMARY

Fire safety in the United States has been the subject of numerous studies over the years. When one reviews these studies and fire history, it becomes obvious that the major contributing factors to large losses, deaths, and injuries remain unchanged. Fire safety in the built environment can be achieved only through an effective partnership among the public, design professionals, contractors, and code officials.

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# *UNIT 2: FIRE DYNAMICS AND THE BUILT ENVIRONMENT*

### *OBJECTIVES*

*The students will be able to:*

1. *Explain basic fire behavior chemistry and physics using the following terms as they relate to the built environment:*

    a. *Flashpoint.*
    b. *Boiling point.*
    c. *Flammable limits.*
    d. *Conduction.*
    e. *Convection.*
    f. *Radiation.*
    g. *Oxidizer.*
    h. *Triple point.*
    i. *Basic research.*
    j. *Applied research.*
    k. *Closed system.*

2. *Explain the progression of fire from start to extinguishment using the following terms as they relate to the built environment:*

    a. *Heat flux/transfer.*
    b. *Heat of combustion.*
    c. *Heat-release rate (HRR).*
    d. $T^2$ *fire.*
    e. *Flashover.*
    f. *Backdraft.*
    g. *Fire plume.*
    h. *Ceiling jet.*
    i. *Homeostasis.*

3. *Recognize the factors in building design and occupancy that contribute to fire ignition, growth, and extinguishment.*

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## FIRE DYNAMICS

Before he or she can be fully competent in fire protection and code enforcement, a code official must be able to articulate how and why fires behave the way that they do. This unit provides the basis for the science that justifies much of what you do.

While mankind is believed to have discovered the use of fire 500,000 years ago, it has been only in recent years that research has been conducted into the scientific complexities of the fire environment. This research has given us a limited understanding of the chemical and physical properties that affect fire growth and spread, methods of heat transfer, and smoke and toxic gas production. Research also has continued in the areas of active and passive fire protection systems, such as fire sprinklers and fire resistant barriers, respectively. Together, this knowledge is known as "fire dynamics."

Fire behavior research is a challenging and exciting field. "Basic research" occurs at a number of State and private universities, research laboratories, and Federal facilities. Scientists and engineers try to explain the phenomenon of ignition and the sequence of events that occurs during combustion and fire growth. Different fuels, ignition sources, and scenarios are evaluated to study fire behavior. "Applied research" involves applying and translating the scientific data into day-to-day uses (i.e., better fire sprinkler designs, fire-retardant fabrics and packaging, and materials handling and storage techniques).

Many requirements in building and fire codes are intended to protect life and minimize property damage from unwanted and hostile fires. It is important to understand the fundamentals of fire behavior in structures so functional, aesthetic, and efficient building designs can be matched to the need to protect people and operations within the built environment.

Fire behavior in structures is complicated. Fuels, oxygen, ventilation, compartmentalization, fire protection systems, interior and exterior design, weather conditions, and human activities affect the outcome of a fire. Those in the fire protection field know that even when given the same set of identical circumstances, it is unlikely that two fires will behave the same or have the same result. Although building codes tend to treat structures within the same occupancy classifications as similar, the fire characteristics between and among structures is widely different.

The chemical reaction with physical effects that is called "fire" is a complex and dynamic event, even in controlled laboratory conditions. Thus, code officials must apply their knowledge of fire dynamics with reasoned and experienced judgment to achieve the highest level of fire protection success under destructive and life-threatening conditions.

It is important for the code official to understand the features of architecture and building components that influence fire growth and behavior and to understand how building and fire codes treat these factors.

## MEASURING FIRE DEVELOPMENT

Both basic and applied research rely on "quantifying" values, that is, measuring them in a way that can be compared from one test to another.

In the United States we still prefer the United States System of Measurement that relies on the familiar feet, inches, pounds, Watts (W), degrees Fahrenheit (°F), and British thermal units (Btus). However, most of the test data are recorded in the metric-based International System (SI) of Units including meters, kilograms, Pascals, degrees Celsius (°C), and Joules.

(Many of the figures and tables in this Student Manual (SM) reference both United States System of Measurement and SI Units. A conversion table for these values is found in Job Aid 2.1 in the Appendix.)

With the exception of the kilogram (kg), the conversions listed in the following chart are to base units such as Joule (J) and Watt (W). When considering a building fire, these units are so small that the values must be reported as kilojoules (kJ) or kilowatts (kW). The "kilo" prefix means to multiply the base unit by 1,000. Another prefix that may be used is mega (M). This prefix means to multiply the base unit by 1,000,000.

Table 2-1 provides examples of unit conversions.

**Table 2-1**
**SI Conversions**

| Property | To Convert From | To | Multiply by |
|---|---|---|---|
| Length | Foot (ft) | Meter (m) | 0.3048 |
| | Meter (m) | Foot (ft) | 3.281 |
| Mass | Pound (lb) | Kilogram (kg) | 0.4536 |
| | Kilogram (kg) | Pound (lb) | 2.205 |
| Time | Second(s) | Second(s) | 1.0 |
| Area | Square foot ($ft^2$) | Square meter ($m^2$) | 0.0929 |
| | Square meter ($m^2$) | Square foot ($ft^2$) | 10.76 |
| Volume | Cubic foot ($ft^3$) | Cubic meter ($m^3$) | 0.0283 |
| | Cubic meter ($m^3$) | Cubic foot ($ft^3$) | 35.3147 |
| Energy, work, quantity of heat | British thermal unit (Btu) | Joule (J) | 1054.8 |
| | Joule (J) | British thermal unit (Btu) | 0.000948 |
| Power, heat release rate | British thermal unit per minute (Btu/min) | Watt (W) =J/s | 17.573 |
| | Watt (W) =J/s | British thermal unit per minute (Btu/min) | 0.05688 |
| | Watt (W) | British thermal unit per second (Btu/sec) | 0.000947 |
| | Btu/lb | Joule/Kilogram | 2326 |
| Heat flux | British thermal unit per square foot per second ($Btu/ft^2/sec$) | Watts per square meter ($W/m^2$), or, Joules/$m^2$/second ($J/m^2/sec$) | 11364 |
| | Watts per square meter ($W/m^2$), or, Joules/$m^2$/second ($J/m^2/sec$) | British thermal unit per square foot per second ($Btu/ft^2/sec$) | 0.000088 |

*Reference*:* National Institute of Science and Technology (NIST) Special Publication 811, *Guide for the Use of the International System of Units (SI).* Gaithersburg: Author, April 1995. See also the Web site www.convert-me.com/en

Note: There is a variety of free online unit conversion services. Use your Web browser and type in "conversion," or the specific units you want (i.e., heat flux conversions) to find them. The National Fire Protection Association (NFPA) *Fire Protection Handbook* includes a table of conversion factors in its appendices.

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# Activity 2.1

## Making Conversions Work

### Purpose

To gain familiarity with the SI as it pertains to fire behavior.

### Directions

1. Take 20 minutes to work individually on the following questions.

2. Answer each question, and prepare to review your answers in class.

### Questions

1. To convert 7 cubic feet of water to cubic meters, one must multiply the cubic feet by:

_____

_____

2. The ceiling jet of a fire is measured at 980 °C. How hot is that in °F?

_____

_____

3. A fire scientist wants to establish the total latent heat of combustion for a wooden crib weighing 144 pounds. In order to enter data into her fire model, she must convert this amount to kilograms. How many kilograms are in half of this crib?

_____

_____

4. Gasoline has about 18,000 Btus of energy potential per pound of product. A gallon of gasoline weighs about 6.8 pounds. What is the total potential energy (in SI units) of 7.46 gallons of gasoline?

_____

_____

5. In 4 minutes, 6 pounds of shredded newspaper will be consumed completely by fire. What is the rate of heat release in SI units for the newspaper?

_____

_____

## CANDLES AS AN EXAMPLE OF FIRE BEHAVIOR

Fire research has a long and storied history. As long as humans have observed the environment, they have tried to explain how it works.

In 1826, Michael Faraday began a series of lectures during Christmas holiday at the Royal Institute in England. The lectures were presented to young adults and focused on science. In 1860, he presented one of his more famous lecture series, *The Chemical History of a Candle.* The lecture described the working phenomenon of candles with a level of understanding of the properties of heat transfer that is comparable to our knowledge of the subject today.

To open our study of the principles of fire dynamics, we will use Faraday's evaluation of the burning process of a candle, which is an excellent model of a laminar diffusion flame.[1] As you read this, think about the times you have looked closely at a burning candle.

Lighting the candle wick results in a sustained flame on the wick. Radiated heat from the flame begins to soften and melt the paraffin wax [a hydrocarbon ($C_{20}H_{42}$)]. The melted wax is drawn up the wick by capillary action (Faraday called this "capillary attraction"). When the liquid wax is exposed to the high temperatures of the flame, it is vaporized into a combustible fuel. Vaporizing the paraffin wax (the process of pyrolysis) occurs in the lower portion of the flame, where the liquid wax meets the flame. The rising vapors of paraffin wax then are consumed in the combustion process of the flame. The candle flame rises upward as a result of the principle of buoyancy, since the combustion gases and heat given to the flame are warmer and lighter than the surrounding (room air) atmosphere. The process continues and is accentuated by the fresh incoming air drawn into the flame region to fill in for the rising products of flame combustion. This process permits a continual supply of oxygen into the diffusion flame of the candle.

The candle flame has several distinct areas that are distinguishable by the change in color within the flame plume. As the paraffin is vaporized, it rises up into the flame region and is premixed with the fresh oxygen coming in from the sides and below the flame. This causes the bottom section of the flame to appear blue. The proper fuel-air ratio in this area results in clean combustion, with little soot. This fuel-rich vapor has not begun the process of being broken down by the heat of the flame.

The darker luminous zone that comprises the inner bottom half of the candle flames is the region where the chemical bonds of the paraffin fuel are broken down by the actions of heat. This permits the pyrolized paraffin fuel to mix with atmospheric air as the pyrolized fuel migrates toward the oxygen and forms a mixture. The mixing action of the fuel and oxygen, seeking to equalize themselves (diffuse) with their surrounding environment, follows the principles of Fick's Law.

Fick's Law states, "…a given species (e.g., in connection with fire, oxygen, fuel, $CO_2$) will move from a high to low concentration in the mixture." For example, a drop of blue ink in a glass of water eventually will diffuse into the water to give a blue tinge. Oxygen in air will move to the flame where it has a concentration of 0 percent as it is consumed in the reaction. Fuel is transported into the opposite side of the flame by the same process. The combustion products diffuse away from the flame in both directions.

[1] "Laminar diffusion flame" describes a smoothly burning candle flame in a well-ventilated environment.

The yellow-to-white luminous zone of the candle is the region where soot (carbon atoms) is present and produces luminosity as the combustion with oxygen. Unburned carbon atoms eventually will escape the high temperature of the flame zone and combine with oxygen ($O_2$) to form carbon dioxide ($CO_2$). A lighter halo exists around the majority of the flame, almost translucent in appearance. This area is the outermost region of combustion, where oxygen and pyrolized paraffin mixes efficiently with very little soot present.

## LAWS OF CONSERVATION

The laws of conservation are fundamental principles of mechanics that serve as the guiding basis for all branches of science. We will discuss briefly these principles so that you will have a better understanding of the foundations that support the complex relationships developed by scientists and engineers and how they apply to the built environment.

Scientists use certain terms as a means of communicating their ideas about universal theories, and we will review a few of these prior to examination of the laws of conservation and thermodynamics. A **system** is defined as the portion of our universe that we are interested in studying. The **system** generally will have prescribed confines (boundaries) and matter (objects or mass) within it.

In order to isolate a particular phenomenon that is being studied, the **system** most often is considered "closed." A **closed system** is isolated from the effects of the outside world, with matter and energy remaining constant within it, and the effects of gravity and other energy and matter are shut out. A hypothetical room with no windows or doors and containing a known amount of combustible items and air volume would represent a closed system. An **open system** permits exchange of matter and energy between it and the outside **surroundings**, so the system can gain and lose energy and/or matter over time. A room with an open window and door that entrains fresh air from outside, and ventilates products of combustion and heat to the outside would be considered an **open system**. When the **system** and its **surroundings** are combined together, they form the **thermodynamic universe** for the particular process under review.

## CONSERVATION OF MOMENTUM

A system's total momentum ($m_{ass}$ times $v_{elocity}$) is said to be constant or "conserved." At any time, the sum of the momentum of all objects within a system will remain constant. (Total momentum=$mv_1+mv_2+mv_n$). If we observe momentum in one direction of the system, then there must be an equal force in the opposite direction. Conservation of momentum accounts for the symmetry that is observed in our world. Sir Isaac Newton developed his Laws of Momentum that explain much of what we know about in the study of physics:

**Newton's First Law**: An object will remain at rest, or in motion in a straight line, unless it is acted upon by an external force. Set a small rubber ball on a table and it won't move. Tilt one end of the table (the external force) and the ball will start to move. As long as the table surface is smooth, the ball will travel in a straight line.

**Newton's Second Law**: A change in an object's motion will result in an increase in acceleration. As the ball described above rolls across the table surface, it will pick up speed at a steadily increasing rate.

**Newton's Third Law**: All internal forces of a system are generated in opposite pairs, so the acceleration of the center of mass of an isolated system is zero. This is the law of "equal and opposite" actions. The amount of energy needed to lift the table is equal to the energy created by the rolling ball (less the influence of friction caused by the table and the air.)

## PRINCIPLES OF THERMODYNAMICS

### Energy

Energy is defined as the capacity to do work, or extract heat. Energy is expended in order to move an object from one point to another, or raise the temperature of a system. Energy may appear in various forms, and either is stored (potential energy), or in motion (kinetic energy), or the potential energy between molecules of a substance (internal energy). The law of conservation of energy states that at any moment in time, the sum of the potential and kinetic energy of any object remains the same. Examples of potential and kinetic energy:

| Potential Energy | Kinetic Energy |
|---|---|
| Electric battery (electric energy) | Electron transfer to power electric windows |
| Water stored in a water tower | Running water from shower |
| Diesel fuel in vehicle tank (chemical) | Powers internal combustion engine |
| Steam (thermal) | Powers steam turbine |

### Conservation of Energy

The energy (or capacity to do work) within a system remains constant. Energy is neither created nor destroyed but can be transformed from one form to another, and the total energy of the system remains unchanged. The process of combustion decomposes a substance with the energy of the chemical bonds of the substance released as heat energy and products of combustion.

Think about the candle observation: potential energy (paraffin wax) is converted to heat energy in the flame. The heat energy excites the air molecules in the atmosphere causing buoyancy. The energy is transferred from the paraffin to the moving air.

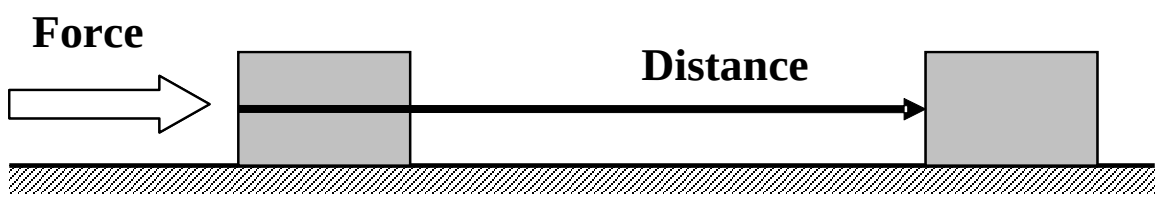
Think about holding a rubber ball in your hand and dropping it onto a ceramic floor. The ball will bounce off of the floor and continue to bounce, the height of each bounce somewhat less than the one before, until all motion ceases and the ball rests on the floor.

The ball held in your hand has stored potential energy, due to its height and the pull of gravity. Once the ball is dropped, the stored potential energy is converted to the kinetic energy of the fall. After striking the floor, the ball begins to rise, gradually losing its kinetic energy and having potential energy (pull of gravity) to fall again. At any point in time, the total sum of the potential and kinetic energy, and friction of compression, sound energy, and floor resistance are theoretically equal.

When the ball ceases to move, the energy that provided the initial movement has been converted to thermal energy as a result of the processes of compression of the ball as it bounces, and friction from the interaction with the floor. The ball's original kinetic energy has been converted into thermal energy stored within the ball and in the floor.

## Work

Work is defined as the product of the external force on a body (mass) and the distance that the force acts. The diagram is true for constant applications of force. If a body does not move when a force is applied, then we cannot say that work has occurred. If the object moves in a direction that is not consistent with the applied force, then work is still accomplished, but only in the length and direction of the result. The work can be measured by multiplying that force times the distance: A block that is moved 5 meters by an applied force of 8 Newtons is the equivalent of 40 joules (mN) of work




**Work=Force**(pounds or Newtons)x**Distance**(feet or meters)

**Figure 2-1**
**Visualization of Work Performed**

Power is a term that describes **a rate of doing work** or using energy. Velocity is a dimension involving time and distance. In cases of where the force is constant and inline with the direction of the velocity, the formulas for power are

SI: $P_{ower}$=Newtons x meters/second=Joules/second=Watts

U.S.: $P_{ower}$ = pounds x feet/second=ft lb/s=horsepower (hp)

If the force is not in line with the direction of the velocity then the formula for instantaneous power is the product of the force and velocity times the cosine of the angle between the two:

$$P_{instantaneous}=F_{orce} \text{ x } \cos\theta \text{ v}$$

Why is the study of work important to the fire protection professional? Many fire protection systems, such as fire pump drivers, measure their output performance using work-based units.

## Heat

**Heat** is expressed or defined as the **process** of transfer of energy from systems or objects of higher temperature to ones of lower temperature. The term **heat** describes an energy transfer resulting from a difference in temperatures of various objects. Objects do not contain heat, rather they possess internal energy. It is incorrect to state that objects or systems possess "heat." Objects having higher energy transfer the energy to objects of lower energy. The process of "sharing" or losing some of an object's internal energy is perceived as thermal heat, or a process of **heating**.

**Temperature** is a measure of the heat generated from the kinetic energy within a system or object. Depending upon the application, temperature is measured in degrees Fahrenheit (F), Celsius (C), Rankin (R), or Kelvin (K). Temperature is not a measure of the object's total energy. Two objects with the same temperature, coal and water for example, will not have the same internal energies, or specific heat values (ability of substance to store energy).

## Work, Heat, and Energy

The **calorie** is the unit of heat energy in the metric system (SI). Heat measurement is called **calorimetry**. A calorie (or gram calorie) is the amount of heat required to raise the temperature of one gram of pure water one degree Celsius (°C). One kilocalorie will raise the temperature of one kilogram of water one °C.[2]

**Heat** and **work** are both capable of transferring energy to systems. If we heat and compress two equal volumes of air, our measurement of the final state of internal energy cannot distinguish which process (or combination of processes) created the increased internal energy. In 1843, James Joule performed an experiment which showed that one calorie of heat equaled 4.186 joules of mechanical energy, proving that there was a relationship between work and heat energy. Refer to Figure 2-2 on the next page.

[2] In U.S. measurements, a Btu is the amount of energy needed to raise the temperature of one pound of water one degree Fahrenheit.

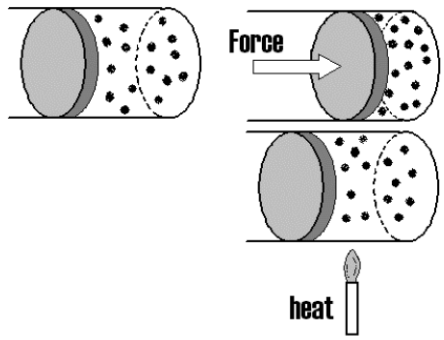



**Figure 2-2**
**Increased Internal Energy Results from Work or Heat**

Automobile engines are good examples of how heat and work transfer energy: a diesel-fueled engine relies on the compression of the fuel to create combustion, a gasoline engine employs heat in the form of a spark to ignite the fuel.

## THERMODYNAMIC LAWS

The **First Law of Thermodynamics** is the application of the conservation of energy principle applied to heat and the thermodynamic process. The change in internal energy in a system is equal to the heat that is added, minus the work performed. When work is performed, the internal energy of a system usually is decreased.

As one liter of fuel is consumed to run a motor vehicle (work being performed in an open system), the total stored energy of the fuel is reduced (amount of fuel being burned).

The **Second Law of Thermodynamics** addresses the efficiency of heat engines and constraints on the direction of heat transfer. According to this law, it is impossible to extract heat from a warmer body and perform work without having some of the energy lost to a colder body. Otherwise, it is impossible to have a heat engine that is 100-percent efficient.

**Thermal equilibrium** is reached when a higher temperature object or system is in contact with a lower temperature system or object. Heat will flow from the warmer system to the colder one, resulting in **thermal equilibrium**. We see this principle at work when a fire-resistive barrier such as a masonry firewall heats up when exposed to a fire.

### Stoichiometric Reactions

The study that examines the relationships between the masses of the reaction substances, and the resulting products is called **stoichiometry**. The term is derived from the Greek words **stoicheion**, meaning "element," and **metron** meaning, "measure". Every fuel-air mixture has an optimum ratio at which point the combustion of the fuel will be complete. This occurs at or near the mixture

known as the stoichiometric ratio. At this point the amount of air is in balance with the amount of fuel. Except for certain types of gas fires, this condition rarely occurs in fires outside a controlled environment like a laboratory.

## The Ideal Gas Law

The Ideal Gas Law may be described as the condition where all collisions between gas molecules or atoms of identical particles of zero volume are elastic, and there are no internal molecular forces or attractions. The gas molecules of this hypothetical **ideal gas** are a group of spheres that can collide, but do not react with each other in any other way.

All internal energy is in the form of kinetic energy (motion) and changing the kinetic energy of the gas results in a change in temperature. As the gas molecules collide with the sides of the container, a kinetic pressure is created. The Ideal Gas Law infers that the measurement of this pressure, which results from the kinetic activity, is therefore proportional to the temperature.

Real gases such as methane, carbon dioxide, hydrogen, or argon do not behave exactly this way, but the principle is similar. The behavioral connection between ideal and real gases breaks down at high pressures and low temperatures, where the intermolecular forces play a greater role in determining the properties of the gas.

The three variables that express the state of an ideal gas are all measurable properties. It is inconsequential as to how the gas molecules reach the measured "state." The state of change may be due to the application of either work or heat, as noted in the above example.

Scientists have established a standard reference point called Standard Temperature and Pressure (STP) relative to expressing and comparing properties and values of ideal gases.

STP is 0 °C (32 °F) at 1 atmosphere (760 mmHg). One atmosphere is the weight of atmospheric air at sea level. In U.S. units, it is 32 °F at 14.7 psia. An atmosphere is abbreviated as "atm."

What is psia? It is scientific shorthand for "pounds per square inch absolute." Absolute pressure is the sum of atmospheric pressure and gauge pressure. Typically we measure tire pressure with an air gauge. The air pressure gauge measures pressure in excess of what the atmosphere provides and is translated as "psig," or pounds per square inch gauge. If we attempt to measure the pressure of a flat tire, the tire pressure gauge would read "zero." This measurement doesn't account for the pressure exerted by the earth's atmosphere. Pressure on a tire gauge equals the **absolute pressure** minus the **atmospheric pressure**. Fire protection system gauges (fire pumps, standpipes, sprinklers, water mist, etc.) generally read in psig values.

Another scientific reference point may be found in the codes when reviewing requirements for gaseous hazardous material use, storage, and handling: Normal Temperature and Pressure (NTP). Normal Temperature and Pressure is 21 °C (70 °F) at 1 atmosphere. NTP is used for comparing characteristics of hazardous materials because they seldom occur in the built environment at Standard Temperature and Pressure.

## Boyle's and Charles's Laws

Two other important scientific rules are Boyle's Law and Charles's Law. If the gas temperature remains constant, then the relationship between pressure and volume is described using Boyle's Law. Boyle's Law states that at a **constant temperature**, the volume of a fixed amount of gas is inversely proportional to pressure. Therefore, if the temperature remains constant, as the pressure goes up, the volume goes down and vice versa.

Boyle's Law is used commonly to predict the result of introducing a change, in volume and pressure only, to the initial state of a fixed quantity of gas. The "before" and "after" volumes and pressures of the fixed amount of gas, where the "before" and "after" temperatures are the same (heating or cooling will be required to meet this condition), are related by the equation:

$$P_{after}\ V_{after}=P_{before}\ V_{before}$$

Where

P = Pressure
V = Volume

On the other hand, if the gas **pressure** remains constant, then the derivation may be referred to as **Charles's Law**. At constant pressure, the volume of a given mass of an ideal gas increases or decreases by the same factor as its temperature (in degrees Kelvin) increases or decreases. The mathematical formula for Charles's Law is

$$V_{after}\ /T_{after\ (K)}=V_{before}\ T_{before\ (K)}$$

Where

T = Temperature
V = Volume

The **Bernoulli Principle** also is a consideration when examining gas flows from a fire. Daniel Bernoulli (1700-1782), a Swiss mathematician, theorized that as the velocity of a fluid increased, the pressure decreased. Bernoulli's Principle proves that gas velocity and pressure are proportional to their product. When gases reach a point of obstruction, a velocity increase is required to maintain the flow. If the velocity of the gas increases, then the pressure will decrease accordingly.

If the Bernoulli Principle is applied to fire gases exiting at a ventilation opening, we should expect an increase in velocity. An increase in temperature inside a closed structure normally will result in an increase in pressure. When the fire gases exit the structure through an opening (such as a window) lower pressure is encountered; therefore, according to Bernoulli's Principle, the velocity of the gas should increase. This accounts for observations of fire gases "shooting" out of openings, and

helps us understand how to design fire protection features to deal with the velocities. These laws are used in fire behavior studies as well as understanding how hazardous materials behave in the environment.

### Triple Point

In physics and chemistry, the **triple point** of a substance is the **temperature** and **pressure** at which three **phases** (**gas**, **liquid**, and **solid**) of that substance may coexist in **thermodynamic** equilibrium.

The triple point of $CO_2$--a common gaseous fire suppression agent--occurs at a pressure of 5.2 atm (3,952 mmHg) and 216.6 K (-56.4 $^oC$). At temperature of 197.5 K (-78.5 $^oC$), the vapor pressure of solid $CO_2$ is 1 atm (760 mmHg). This information is useful for designing $CO_2$ systems for special hazards.

## WHAT IS FIRE?

### The Fire Triangle and Tetrahedron

Fire is a chemical reaction that produces physical effects: heat, light, and material decomposition. In the simplest of terms, the components of "fire" can be illustrated by the fire triangle. The sides of the triangle represent heat, fuel, and oxygen. In addition to the heat, fuel, and oxygen, there also is the uninhibited chemical chain reaction. Some authors describe these conditions as a four-sided object, the fire tetrahedron:

- **Heat**: the energy needed to ignite a combustible fuel. It may be natural or manmade.
- **Oxygen**: the gas needed to sustain combustion. It may occur freely in nature (the atmosphere is about 21 percent oxygen) or be introduced from some other chemical (an oxidizer).
- **Fuel**: a material that will convert from a solid, liquid, or gas and release energy during the process.
- **Uninhibited chain reaction**: the chemical process that sustains combustion without interruption.

While these elementary depictions are sufficient for many situations, a more detailed understanding of the chemistry and physics of fire is necessary to explain how fire and smoke behave in a building. Understanding these phenomena enable design professionals and code officials to apply both prescriptive and performance-based designs, codes, and fire protection systems and equipment correctly.

Fire may be an essential part of an industrial process or residential heating appliance, but, once there is a failure, a fire may become hostile rather than beneficial. Unwanted fires pose a serious threat to life and property if they are not confined or extinguished.

## COMBUSTION PROCESSES

In the precombustion phase of fire, fuels may be heated to their ignition temperature from a variety of sources. Ignition temperature is the minimum temperature a substance must attain in order to ignite under specific test (laboratory) conditions. Heat is the energy that is needed to maintain a change in temperature. Temperature is the measurement that expresses the degree of molecular activity of a material compared to a reference point such as the freezing point of pure water.

### Pyrolysis

During the precombustion phase, vapors and solid particulate matter are being released from the fuel. These materials commonly are called pyrolysis products or pyrolyzate. Pyrolysis is the transformation of a material into one or more other substances by heat alone. Glowing combustion or smoldering may or may not be related to the oxygen level. Such glowing can occur during both the initial and final stages of a fire. While a limited oxygen level may result in smoldering, such conditions also can be created by the amount of fuel vapor production or temperature.

Flaming combustion occurs when there is sufficient energy (heat), fuel vapors in the flammable range, and adequate oxygen. The chemical reaction must be unimpeded if the fire is to continue. These phases may exist individually or simultaneously in any given fire.

#### Diffusion Flame Process

During flaming combustion, the flames are either **diffused** or **premixed**. In most structural fires the pure fuel vapors are released and diffused or mixed with the surrounding air (oxygen). This mixing process is known as diffusion. If the fuel vapors and air mixture fall with the flammable range and an ignition source is present, ignition will occur. Flames, which are the result of this mixing of fuel vapors and air, are known as diffusion flames.

#### Premixed Flame Process

Premixed combustion occurs when the fuel vapors/gases are mixed in advance with an appropriate quantity of air or oxygen to form a mixture prior to ignition. Premixed combustion occurs during an explosion, but most commonly occurs with gas-fired appliances or industrial processes. Premixed combustion is typically more efficient and produces less smoke than diffusion flames.

## THE IGNITION PROCESS

The traditional approach to fire and life safety is based on the assumption that a single episode of unwanted ignition will occur, and the building and fire protection features will minimize the impact of the result. Fire-resistive construction, compartmentalization, fire detection, and fire sprinkler systems "react" to the fire and--if all work properly--confine, report, and control the fire to some manageable level. If the fire is not suppressed by the fire protection system or timely occupant action, the local fire authorities may be called to intervene. Fire protection codes and protective

inspections are intended to prevent fires from occurring, but if they do, the built environment is called upon to perform.

## Ignition Types

Ignition is that sequence of events that brings environmental fuels, oxygen, and a heat source together in adequate proportion to start a fire. Much of the content of fire prevention codes is based on ignition prevention: keeping flammable or combustible fuels away from heat sources.

When evaluating a building or facility, design professionals and code officials must examine closely the potential types of ignition that might occur based on the operations, processes, and storage that will exist. They are

- **Autoignition** that occurs when the fuel is heated sufficiently for the vapors to ignite without the presence of any outside arc, spark, ember, or open flame. Compressive and percussive forces often are adequate to ignite fuels.

- **Piloted ignition** that occurs when an arc, spark, ember, or open flame ignites fuel vapors. The amount of energy (heat) required for piloted ignition is less than that necessary for auto-ignition. This is because the "pilot" is igniting vapors, rather than heating the solid fuel.

- **Spontaneous heating to ignition**--often called "spontaneous combustion"--is a form of autoignition. Certain fuels are or can become "self-heating." This process commonly is known as spontaneous heating. This is a process whereby a material increases in temperature without drawing or absorbing heat from its surroundings. The incubation process results from oxidation, often aided by bacterial action when agricultural products are involved. Under the right conditions, the self-heating can generate sufficient temperatures for ignition to occur. When ignition occurs as a result of spontaneous heating, it is known as "spontaneous ignition." Table 2-2 shows some of the materials that are subject to spontaneous heating and ignition.

**Table 2-2**
**Partial List of Materials Subject to Spontaneous Heating and Ignition**

| | |
|---|---|
| Alfalfa meal | Used burlap bags |
| Castor oil | Charcoal |
| Coal | Coconut oil |
| Cod liver oil | Cornmeal feeds |
| Cottonseed | Fishmeal |
| Foam rubber | Linseed oil |
| Metal powders | Peanuts/Oil |
| Powdered eggs | Powdered milk |
| Powdered latex gloves | |

## Ignition Temperatures

Different fuels have different ignition temperatures: the temperature to which they must be heated to sustain combustion. Unfortunately, laboratory-established ignition temperatures might not be replicable outside of scientifically-controlled conditions in the "real" world. Due to the wide range of variables that can exist outside the lab, ignition temperatures should be regarded solely as approximations.

Variables affecting ignition temperature include the rate and duration of fuel heating, the shape and volume of the test container, the kind and temperature of the ignition source, airflow, and the variables of contaminants in the fuels. Fuels found in the environment seldom are as pure as those tested in a laboratory.

Some products will self-ignite if they are heated to their autoignition temperature. Table 2-3 provides examples of common products and their autoignition temperatures.

**Table 2-3**
**Autoignition Temperature of Common Fuels**

| Material | Autoignition Temperature | |
|---|---|---|
| | °F | °C |
| Acetone | 869 | 465 |
| Ammonia | 928 | 498 |
| Butane | 550 | 288 |
| Ethane | 882 | 472 |
| Ethanol | 685 | 363 |
| Gasoline (varies based on octane rating) | 536 to 880 | 280 to 471 |
| Methane | 999 | 537 |
| Methanol | 725 | 385 |
| Octane | 403 | 206 |
| Propane | 842 | 450 |
| Toluene | 896 | 480 |

Source: NFPA *Fire Protection Handbook*, 18th edition, p. 3-34.

For piloted ignition to occur, a "competent" ignition source must be present. A competent ignition source is one that has both sufficient temperature and energy to raise a fuel to its ignition temperature during the contact period. While the temperatures of many potential ignition sources exceed the ignition temperature of common fuels, the ignition source must last long enough, and be in contact with the fuel long enough, to raise the fuel to its ignition temperature.

For example, a 110/220-volt electrical arc results in temperatures in the 6,000 to 10,000 °F (3,316 to 5,538 °C) range; however, in most instances, the event is extremely short lived and the contact period is limited. Unless the arc occurs in the presence of flammable vapors or other volatile material, ignition most likely will not occur.

This is a key principle of fire protection in many industrial occupancies: keeping electrical arcs away from flammable vapors or dusts to prevent fires or explosions. NFPA 70, *National Electrical Code*® and the model fire codes "classify" hazardous areas based on the fire or explosion potential. Once the boundaries of the hazardous area are defined--for example the interior of a spray booth--the electrical code specifies "explosion proof" or "enclosed" wiring and devices must be used. The size and shape of the classified areas varies depending upon factors like fuel volatility and ventilation.

Table 2-4 provides examples of fuels and their range of ignition temperatures.

**Table 2-4**
**Ignition Temperatures of Some Materials**

| Material | Ignition Temperature | |
|---|---|---|
| | °F | °C |
| Ammonia (refrigerant) | 1,210 | 654 |
| Asphalt | 905 | 485 |
| Cotton | 750 | 400 |
| Cottonseed oil | 650 | 343 |
| Ethanol | 798 | 425 |
| Gasoline (100 octane) | 824 | 440 |
| Kerosene (Fuel Oil No. 1) | 410 | 210 |
| Natural gas | 900 to 1,170 | 482 to 632 |
| Paper newsprint (cuts) | 450 | 232 |
| Polyester fiberglass composite wall panel | 830 | 443 |
| Polyethylene construction material (rigid) | 824 | 440 |
| Polypropylene siding, rigid | 651 | 344 |
| Polystyrene concrete forming unit | 698 | 370 |
| Polyvinyl chloride soffit material (rigid) | 752 | 400 |
| Recycled plastic/wood waste lumber substitute | 698 | 370 |
| Refrigerant, home air-conditioner (hydro-fluorine) | 386 | 198 |
| Refrigerant, home air-conditioner (hydro-carbon) | 1,585 | 863 |
| Urethane foam | 852 to 1,074 | 456 to 579 |
| Wood (fir, oak, pine, etc.) | 378 to 507 | 192 to 265 |

Source: NFPA 325, *Guide to Fire Hazard Properties of Flammable Liquids, Gases and Volatile Solids*; various product Web sites.

## Fuels

Fuels may be materials used for the construction of the structural frame of the building, its interior finishes, and its contents. Fire behavior is affected by both the available fuel and air or oxygen. Fuels may exist in the solid, liquid, or gaseous state, but only the vapors actually burn. For flammable liquids and gases, adequate concentrations of vapor may exist in their natural state that

would enable piloted or autoignition to occur. For solids, pyrolysis releases vapors from the solid surface where they can mix with adequate quantities of air or oxidizers to sustain combustion.

Fuels that normally exist in a gaseous state and those that produce sufficient vapors at normal ambient temperatures (flammable liquids, e.g., gasoline or liquefied petroleum gases, e.g., propane or butane) present a higher hazard since no preheating is necessary for combustion to occur in the presence of a competent ignition source. The development of a fire depends on the fuel and its state, the location and geometry of the fuel, and the ventilation.

## Fuel or Fire Loading

Traditionally, fuel's potential energy has been expressed in pounds or kilograms, such as a value of 8,000 Btus per pound (18,608 J per g). This method does not reflect the **rate** at which the fuel will burn, but is limited to the **amount of potential energy** available. Nowadays, though, many building components and furnishings employ hydrocarbon-based constituents. Studies show the potential heat energy of these products may be as high as 16,000 to 24,000 Btus per pound (37,216 to 55,824 J per g).

"Fire load" is the amount of fuel per square foot (or $m^2$) generally within a structure. This is an important value because the design principle of most fire suppression systems is to provide enough heat absorbing agent--such as water from a sprinkler system--to control the heat output. If the heat output exceeds the cooling capacity, the fire will destroy property. If the fire suppression system--including water from firefighter's hoselines--can control the heat output, the fire will be extinguished.

As an example, a fire sprinkler system designed to protect a warehouse full of metal equipment in wooden crates needs less water than one protecting a similar building full of upholstered furniture wrapped in plastic because the heat output in the latter scenario would be greater than the former.

## Flammable or Explosive Limits

For any ignition to take place, the fuel must be heated sufficiently to produce enough vapors that, when mixed with air, fall within the flammable or explosive range/limit. Flammable limits are the upper and lower concentration limits of a vapor or gas in air that can be ignited. Flammable limits also may be known as "explosive limits," "explosive range," or "flammable range." Several factors, working together, affect whether or not sufficient vapors will be produced in quantities needed to create a flammable range. These factors include the temperature and energy of the heat source and the thermal properties, density, and heat absorbing capacity of the material (fuel).

Flammable ranges are important considerations in those occupancies where flammable or combustible liquids or gases are used, processed, dispensed, or stored. One recognized mitigation strategy to prevent fires in these environments is to provide natural or mechanical ventilation adequate to prevent vapor air concentrations within their flammable range.

Table 2-5 provides a sample of common products and their laboratory-established flammable limits.

**Table 2-5**
**Common Product Flammable Limits**

| Material | Lower Flammable Limit (%) | Upper Flammable Limit (%) |
|---|---|---|
| Acetone | 2.5 | 12.8 |
| Acetylene | 2.5 | 100 |
| Benzene | 1.2 | 7.8 |
| Carbon monoxide | 12.5 | 74 |
| Ethylene | 2.7 | 36 |
| Gasoline | 1.4 | 7.6 |
| Isobutane | 1.8 | 8.4 |
| Propylene glycol | 2.6 | 12.5 |
| Toluene | 1.1 | 7.1 |

Source: NFPA 325, *Guide to Fire Hazard Properties of Flammable Liquids, Gases and Volatile Solids.*

## Flashpoint and Boiling Point

Unit 6 of this course, Hazardous Materials: Recognition and Control, addresses hazardous materials in greater detail. Two of the important concepts that the code enforcement official must understand to apply hazardous materials regulations correctly are "flashpoint" and "boiling point" or "boiling temperature." Both of these physical characteristics must be assessed when the code official deals with flammable and combustible liquids.

Flashpoint is the temperature at which a liquid fuel emits adequate vapors that a spark will ignite the vapors, but not sustain combustion. Like other products, flashpoint temperatures are established by tightly controlled laboratory tests and their application in the "real" world should be evaluated carefully.

Boiling point, or temperature, is the temperature at 1 atm where the liquid's vapor pressure equals the atmospheric pressure. Once a liquid's vapor pressure **exceeds** atmospheric, the liquid will begin to boil.

Flashpoint and boiling point are used in conjunction to classify flammable and combustible liquids for correct fire code regulations. This will be discussed in Unit 6.

Note: As with any hazardous materials analysis, the code official should consult at least three sources of information, including product Material Safety Data Sheets (MSDSs), independent consultants and chemists, product manufacturers, the local hazardous materials response team, or other reliable sources, before evaluating mitigation plans.

## Heat Energy

Fuel or fuel loading essentially is a description of a material's "heat of combustion." The "heat of combustion" should not be confused with the heat-release rate (HRR) discussed next. Heat of combustion is the total Btu (caloric) value that can be extracted from a fuel under perfect conditions. Heat-release rate pertains to the speed at which combustibles will burn.

The heat of combustion is influenced both by the physical form of the fuel and its chemical composition, also known as fuel chemistry. This simply represents how much energy the fuel would release if completely consumed. It does not reflect the release over any specific time period.

Consider a cut Christmas tree as an example. A typical tree weighs about 12 pounds (5.472 kg). Given an average value of 8,000 Btu per pound (18,608 kJ/kg), one would expect this tree to possess about 96,000 Btus (223,296 kJ/kg) of heat energy if fully consumed.

## Construction Materials and Contents

Many of the materials used in the building construction and contents are synthetics or are hydrocarbon based, e.g., plastics. These materials have a much greater energy potential than traditional building materials such as wood. As the chart in Table 2-6 shows, hydrocarbon-based fuels have approximately twice the energy potential as ordinary combustibles.

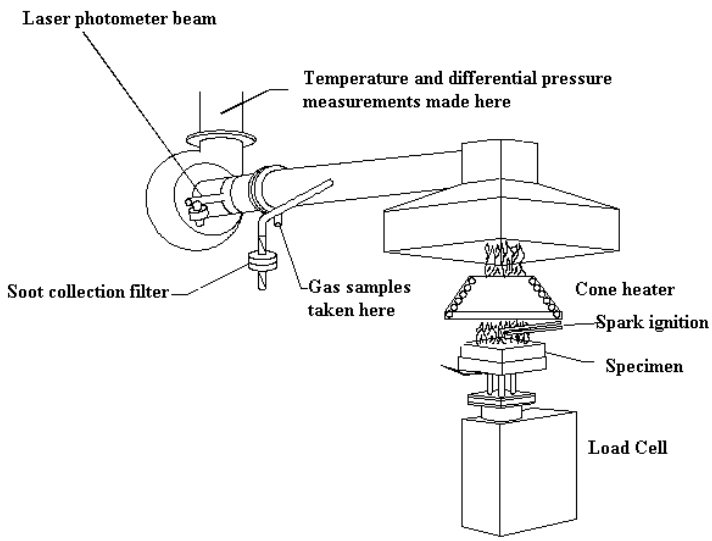
**Table 2-6**
**Energy Potential (Heat of Combustion): Common Combustibles**

| Material | Heat of Combustion (Btu/lb) | Heat of Combustion (kJ/kg) |
|---|---|---|
| Asphalt | 17,150 | 39,890 |
| Corrugated fiber carton | 5,970 | 13,886 |
| Cotton batting | 7,000 | 16,282 |
| Gasoline | 19,250 | 44,775 |
| Oil, cottonseed | 17,100 | 39,774 |
| Paper newsprint (cuts) | 7,883 | 18,336 |
| Paraffin oil | 17,640 | 41,030 |
| Polystyrene | 18,000 | 41,868 |
| Polyvinyl chloride (rigid) | 7,500 to 9,500 | 17,445 to 22,097 |
| Wood (sawdust shavings) | 7,500 to 9,500 | 17,445 to 22,097 |
| Wood--oak | 8,493 | 19,754 |
| Wood--pine | 9,676 | 22,506 |
| Wrapping paper | 7,106 | 16,770 |

Note: SI values are converted to kilojoules. One kilojoule equals 1,000 joules.

## Cone Calorimeter

Heat of combustion values come from controlled experiments with a laboratory device known as a cone calorimeter. The calorimeter measures the oxygen consumed during a fire to establish the heat of combustion. The test procedures also presume 100-percent fuel consumption. While total fuel consumption in the built environment may be feasible for flammable gases or liquids, it is uncommon for solid fuels. Also remember the fuel samples are controlled for moisture, density, weight, and purity, which seldom, if ever, occurs outside the laboratory. Figure 2-3 represents a typical cone calorimeter test apparatus.




*(Image courtesy of National Institute of Standards and Technology, Building and Fire Research Laboratory.)*

**Figure 2-3**
**Cone Calorimeter Test Apparatus**

## Heat Release Rate or Rate of Heat Release

The rate at which a fuel burns and releases its energy is known as the heat-release rate (HRR). Some fire protection texts refer to this as the rate of heat release (RHR). The HRR is determined by multiplying the mass loss rate (mass/time) by the heat of combustion (energy/mass) and the combustion efficiency (the portion of the mass actually converted to energy).

The HRR is a relative measure of a fire's "ferocity." HRR is influenced by the fuel's physical form and its chemical composition, also known as "fuel chemistry." HRR is quantified using the kilowatt (kW).

Remember, HRR is not the same as heat of combustion, since HRR describes release over a specific time period. For example, while a lumberyard fire may appear spectacular with leaping flames and lots of radiant heat, the HRR from a fire in shredded wastepaper like that found at a recycling center is much greater.

A fire that is increasing in energy output is classified as a "growing fire" and the HRR may increase over time. Normally, this type of fire will be fuel-controlled. When the HRR becomes relatively constant over time, with neither a rapid increase nor decrease, the fire is considered to be in a "steady state."

Figure 2-4 graphically depicts a fire transitioning from a "growing state" to "steady state."

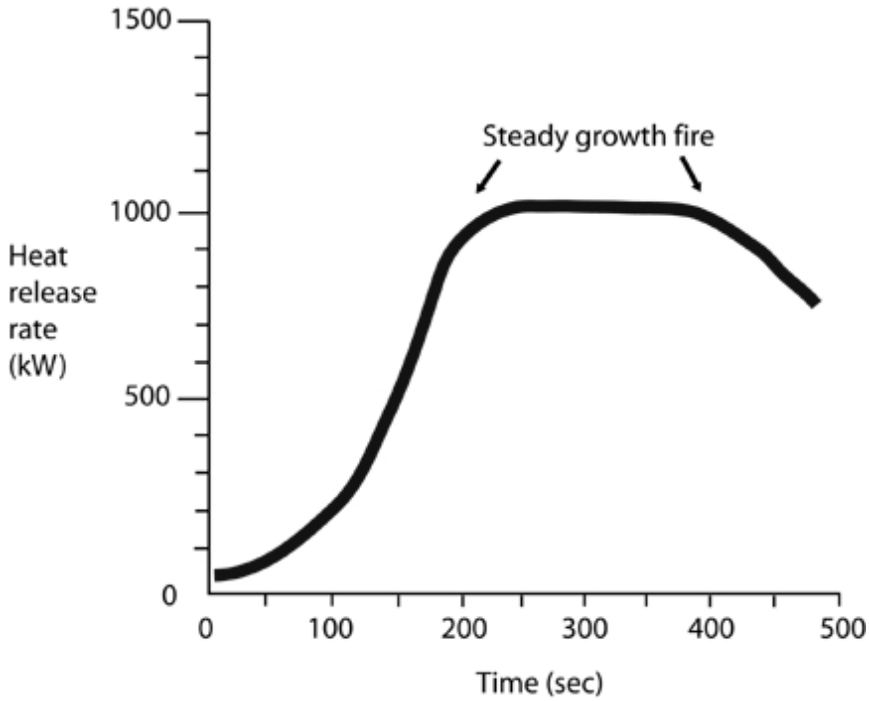
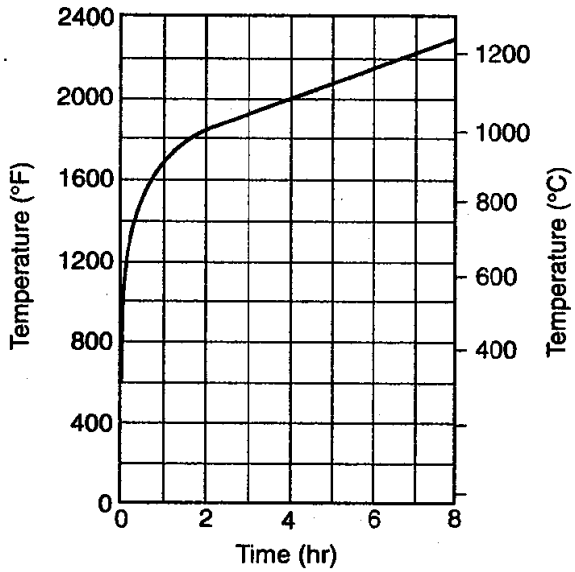



**Figure 2-4**
**Graph of a Growing and Steady-State Fire**

Steady-state fires are the basis for the Standard Time/Temperature Curve (STTC) used for evaluating the fire-resistance performance of common building materials. The STTC was adopted by the American Society for Testing and Materials (ASTM) in 1918, and is the basis for several fire-test standards.




Note: The following are the points that determine the curve.

1000°F ( 538°C).....at 5 minutes
1300°F ( 704°C).....at 10 minutes
1550°F ( 843°C).....at 30 minutes
1700°F ( 927°C).....at 1 hour
1850°F (1010°C).....at 2 hours
2000°F (1093°C).....at 4 hours
2300°F (1260°C).....at 8 hours or over

Source: NFPA 251, *Standard Methods of Tests of Fire Resistance of Building Construction and Material*, 2007 Edition.

**Figure 2-5**
**Standard Time/Temperature Curve**

### The Standard Time/Temperature Curve

It is important for the code official to understand the STTC's significance. Though dated and of questionable validity in today's built environment, it remains the primary method for evaluating building construction fire-resistance ratings.

The selection of building materials and the design of construction details play an important role in building fire safety. Two considerations are

1. Structural frame to avoid collapse.
2. Ability of barriers to prevent ignition and flame spread to adjacent spaces.

Structural collapse potential and fire endurance of beams, girders, and columns that comprise the structure's frame were determined by the ASTM in 1907 using the Standard Time/Temperature Curve, by fire-resistance tests established in 1918 by the NFPA, and by fire-resistance ratings which are commonly referred to as:

- 15 minutes;
- 30 minutes;
- 45 minutes;
- 1 hour;
- 1-1/2 hours;
- 2 hours;
- 3 hours; and
- 4 hours.

Combinations of building materials are put together into an "assembly" and tested in a laboratory to establish fire-resistance ratings. A mockup wall constructed of No. 25 gage carbon sheet steel studs spaced 16 inches apart and covered **on both sides** with a layer of 5/8-inch Type X gypsum wallboard properly attached and having taped joints is just one example of an "assembly."

This assembly is installed in a test furnace and subjected to increasing heat using the Standard Time/Temperature Curve. A 1-hour rating indicates that the assembly survived the standard test for 1 hour or longer, 2-hour rating indicates the assembly withstood a 2 hour or longer test without failure of a critical element. Acceptance criteria are specific and **may** include

- failure to support load;
- temperature increase on the unexposed surface (the side opposite the heat source) 250 °F (121.1 °C) above ambient;
- passage of heat or flame sufficient to ignite cotton waste;
- excess temperature on steel members; and/or
- failure under hose stream applications (walls and partitions).

It is also important to note there is no guarantee that an assembly given a particular fire-resistance rating in the lab will perform the same way in the built environment because of differences in quality of materials, construction, maintenance, fuel, and ventilation, etc. Fire-resistance rating should be looked at as comparisons, a 3-hour assembly likely will survive longer than a 2-hour, a 2-hour longer than a 1-hour, and so on.

## $T^2$ Fires

Fires also can be defined by the time it takes to reach a given HRR. While we base current fire protection decisions on a test procedure a century old, current research shows that most fires grow exponentially, that is, the HRR increases to the square of the burning time. These fires are referred to commonly as "T squared fires." The HRR of the growth phase can be expressed as:

$\bar{Q} = \alpha t^2$
$\alpha$ = fire growth constant usually expressed in kJ/sec $^{(n-1)}$
$t$ = time after ignition beginning with open flaming, normally expressed in seconds

By comparing the $T^2$ fires to the Standard Time/Temperature Curve, it is evident more research needs to be accomplished to assess the performance of fire-resistive construction when exposed to the fuel arrays more commonly seen today.

### Heat Release Rate for Different Types of Fuel

Research also has established fire growth constants ($\alpha$) for four standardized $T^2$ fires as follows:

| Category | Fire Growth Constant kJ/sec $^{(n-1)}$ | Time to Reach 1 mW Heat Release Rate |
|---|---|---|
| Ultrafast | $\alpha$ = 0.1876 kJ/sec$^{(n-1)}$ | 75 sec. or 1.25 min. |
| Fast | $\alpha$ = 0.0469 kJ/sec$^{(n-1)}$ | 150 sec. or 2.5 min. |
| Medium | $\alpha$ = 0.01172 kJ/sec$^{(n-1)}$ | 300 sec. or 5 min. |
| Slow | $\alpha$ = 0.00293 kJ/sec$^{(n-1)}$ | 600 sec. or 10 min. |

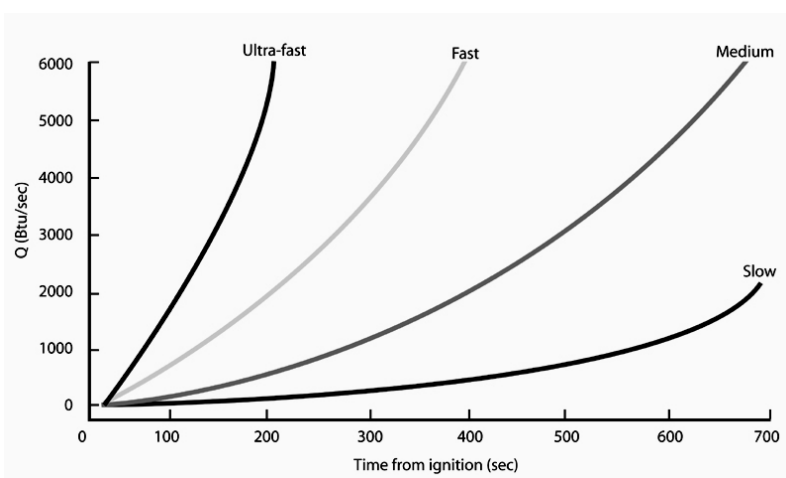



**Figure 2-6**
**Fire Growth Rates for $T^2$ Fires (Btu/sec)**

Examples of these fires shown in Figure 2-6 are as follows:

**Table 2-7**
**$T^2$ Fire Fuel Arrays**

| Category | Fuel Array |
|---|---|
| Ultrafast | Thin plywood wardrobe cabinet; upholstered furniture |
| Fast | 5-ft. high stack of empty wood pallets; 15-ft. high stack of cartons of various contents |
| Medium | 3-ft. high pallet stack of full mailbags; cotton/polyester innerspring mattress |
| Slow | Solid wood cabinetry; wood table; bedroom dresser |

Other examples can be found in NFPA 92B, *Standard for Smoke Management Systems in Malls, Atria, and Large Spaces*.

Figure 2-7 shows the heat release rate for a sofa.

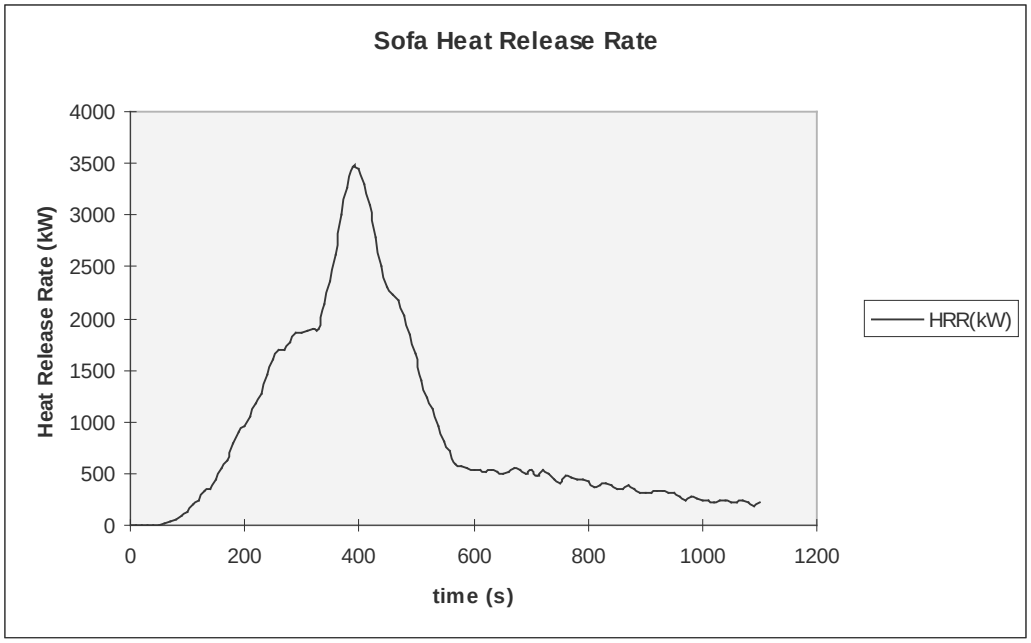



**Figure 2-7**
**Heat Release Rate for a Sofa**

These "standardized" fires should be interpreted with caution. In certain circumstances or conditions, the use of these data would be inappropriate, such as where flammable liquid pool fires are anticipated, or for occupancies such as warehouses or "big box stores."

There still is a lot of research to be done in this field. The complex interrelationships of fuel, ventilation, and geometry mean every fire will be different.

While it is important to study a materials' HRR, another term occurs in fire studies: **peak** heat release rate. This is the point in the fire where the burning material is releasing its maximum heat output. For example, a fire in a pile of waste paper releases a relatively small amount of heat until optimum fuel: oxygen ratios are reached, causing the fire to burn its hottest.

Table 2-8 provides a list of common materials and their **peak** HRRs under laboratory conditions.

**Table 2-8**
**Sample Peak Heat Release Rates**

| Item | Weight (lbs) | Peak HRR (Btu/sec) | Peak HRR (kW) |
|---|---|---|---|
| Burning cigarette | | 0.004739 | 0.005 |
| Burning match | | 0.75828 | 0.08 |
| Small trashcan fire | 1.5 to 3 | 47.355 to 284.13 | 50 to 300 |
| Trashbags, 11 gallon with mixed plastic and paper trash | 2.5 to 7.5 | 132.7 to 331.7 | 140 to 350 |
| Cotton mattress | 26 to 29 | 37.9 to 919.4 | 40 to 970 |
| Televisions sets | 69 to 72 | 113.7 to 274.8 | 120 to 290 |
| Plastic trashbags with paper trash | 2.6 to 1 | 113.7 to 331.7 | 120 to 350 |
| PVC waiting room chair, metal frame | 34 | 255.9 | 270 |
| Cotton easy chair | 39 to 70 | 274.8 to 350.7 | 290 to 370 |
| Gasoline/Kerosene in 2 $ft^2$ pool | | 379.1 | 400 |
| Christmas trees, dry | 14 to 16 | 473.9 to 616.1 | 500 to 650 |
| Polyurethane mattress | 7 to 31 | 767.7 to 2,492.8 | 810 to 2,630 |
| Polyurethane easy chair | 27 to 61 | 1,279.6 to 1,886.2 | 1,350 to 1,990 |
| Burning upholstered chair | | 75.68 to 2,369.6 | 80 to 2,500 |
| Polyurethane sofa | | 2957.3 | 3120 |
| Burning Christmas tree | 12 to 14 | 1,516.5 to 4,928.8 | 1,600 to 5,200 |
| Base Design Fire* | | 4995.7 | 5,275 |

Source: NFPA 921, *Guide for Fire and Explosion Investigations.*

* Minimum HRR design fire for smoke management system design required of the International Building Code (IBC).

## Ventilation

### Atmospheric Oxygen

The third leg of the fire triangle is oxygen. When combined with adequate fuel and a viable ignition source, the introduction of oxygen enables combustion to occur.

In the typical fire, the oxygen source is atmospheric air. The air we breathe consists of about 18 percent oxygen, 72 percent nitrogen, and trace amounts of other gases. The oxygen in air combines readily with fuels to sustain combustion. As long as the oxygen concentration remains above 14 to 15 percent, free-burning combustion can occur. As the amount of oxygen decreases, the quality of combustion decreases with greater production of toxic gases (especially carbon monoxide), soot particles, and smoke.

As the environment in an enclosure deteriorates due to consumption of the available oxygen, dangerous backdraft conditions can develop. A backdraft may occur when oxygen is introduced into a heated, confined space that is oxygen-deficient. The in-rush of oxygen enables the heated combustibles to ignite nearly simultaneously with almost explosive results. In fact, some fire suppression personnel use the term "smoke explosion" to describe a backdraft. During fire operations, firefighters work hard to open windows, doors, and other barriers to relieve smoke buildup before it reaches backdraft conditions.

Generally, in the early stages of fire development, the behavior of the fire is "fuel controlled," that is, there is a sufficient, if not excess, amount of air but a limited fuel supply. In a compartment with little or no ventilation, the fire will continue to grow and may reach a point where the amount of fuel vapors being produced exceeds the amount that can be consumed with the available air or oxygen. A fire that is controlled or limited by the amount of available air or oxygen is "ventilation controlled."

### Oxidizing Agents

In some circumstances, the oxygen portion of the fire triangle may be provided by an "oxidizer," a material that yields oxygen or other oxidizing gas, or that reacts to promote or initiate combustion of combustible materials. These materials support combustion in the absence of atmospheric oxygen. A list of oxidizers may include organic (with molecular carbon) or inorganic chemicals.

These materials have excess oxygen which may be liberated, especially at higher temperatures. This capacity to provide oxygen makes these chemicals a fire and explosion hazard when they come in contact with all forms of combustibles (wood, paper, textiles, plastics, etc.). In addition, mixtures of oxidizers and combustibles can be ignited by a heat energy originating from a weak ignition source such as friction, physical impact, or static electricity. Some of these compounds are capable of reacting with combustibles at room temperature, with the result of a fire and/or explosion. Table 2-9 provides the classifications and a description of the potential hazards.

**Table 2-9**
**Oxidizer Hazard Classes**

| Class Rating | Hazard Description |
|---|---|
| Class 1 | An oxidizing material whose primary hazard is that it may increase the burning rate of combustible material with which it comes in contact. |
| Class 2 | An oxidizing material that will moderately increase the burning rate or which may cause spontaneous ignition of combustible material with which it comes in contact. |
| Class 3 | An oxidizing material that will cause a severe increase in the burning rate of combustible material with which it comes in contact or which will undergo vigorous self-sustained decomposition when catalyzed or exposed to heat. |
| Class 4 | An oxidizing material that can undergo an **explosive reaction** when catalyzed or exposed to heat, shock, or friction. |

Other materials without oxygen in their chemical formula may be classified as oxidizers. To be defined as an oxidizer, the chemical substance simply must be capable of accepting electrons. Chemicals in the class of compounds known as the halogens, materials that can act as halogenating agents, fall into this category. Examples include fluorine and chlorine in the gaseous state, and bromine in the liquid state. Table 2-10 provides a sample of some oxidizing chemicals by hazard class.

**Table 2-10**
**Sample Oxidizers**

| Hazard Class | Sample Oxidizers |
|---|---|
| Class 1 | Aluminum nitrate, potassium dichromate, ammonium persulfate, potassium nitrate, barium chlorate, potassium persulfate, barium nitrate, silver nitrate, barium peroxide, sodium carbonate peroxide, calcium chlorate, sodium dichloro-s-triazinetrione, calcium nitrate, sodium dichromate, calcium peroxide, sodium nitrate, cupric nitrate, sodium nitrite, hydrogen peroxide (8 to 27.5 percent), sodium perborate, lead nitrate, sodium perborate tetrahydrate, lithium hypochlorite, sodium perchlorate monohydrate, lithium peroxide, sodium persulfate, magnesium nitrate, strontium chlorate, magnesium perchlorate, strontium nitrate, magnesium peroxide, strontium peroxide, nickel nitrate, zinc chlorate, nitric acid (<70 percent conc.), zinc peroxide, perchloric acid (<60 percent conc.) |
| Class 2 | Calcium hypochlorite (<50 percent wgt.), potassium permanganate, chromium trioxide (chromic acid), sodium chlorite (<40 percent wgt.), halane, sodium peroxide, hydrogen peroxide (27.5 to 52 percent conc.), sodium permanganate, nitric acid (>70 percent conc.), trichloro-s-triazinetrione |
| Class 3 | Ammonium dichromate, potassium chlorate, hydrogen peroxide (52 to 91 percent conc.), potassium dichloroisocyanurate calcium hypochlorite (>50 percent wgt.), sodium chlorate, perchloric acid (60 to 72.5 percent conc.), sodium chlorite (>40 percent wgt.), potassium bromate, sodium dichloro-s-triazinetrione |
| Class 4 | Ammonium perchlorate, ammonium permanganate, guanidine nitrate, hydrogen peroxide (>91 percent conc.), perchloric acid (>72.5 percent), potassium superoxide |

Source: NFPA 325, *Guide to Fire Hazard Properties of Flammable Liquids, Gases and Volatile Solids.*

## Traditional Fire Stages

Traditionally, fires have been categorized in three basic stages: incipient, free burning, and smoldering. Incipient stage is when there is no active or open flaming. In this stage, glowing or smoldering combustion may be present for a considerable period of time. In the free-burning stage, open flaming is present, with increased fuel consumption and heat production. The last stage, smoldering, occurs when the oxygen level decreases below 14 to 15 percent. If an additional oxygen supply is introduced, the fire may return to the free-burning stage. These descriptions, while helpful in certain circumstances, are not definitive enough for use in performance-based design.

## Fire Realms

Some fire protection texts have established different realms of the fire process. These realms are shown in the chart in Table 2-11 and graphically in Figure 2-8.

**Table 2-11**
**Realms of the Fire Process**

| Realm | Approximate Range of Fire Sizes | Major Factors That Influence Growth |
|---|---|---|
| 1. Preburning/ Precombustion | Overheat to ignition | • Amount and duration of heat flux<br>• Surface area receiving heat from material ignitability<br>• Pyrolyzation rate |
| 2. Initial burning | Ignition to radiation point<br><br>10" (254 mm) high flame | • Fuel continuity<br>• Material ignitability<br>• Thickness<br>• Surface roughness<br>• Thermal inertia of fuel<br>• Pyrolyzation rate |
| 3. Vigorous burning | Radiation point to enclosure point<br><br>10" (254 mm) to 5' (1.5 m) flame | • Interior finish<br>• Fuel continuity<br>• Feedback<br>• Material ignitability<br>• Thermal inertia of the fuel<br>• Proximity of flames to surfaces |
| 4. Interactive burning | Enclosure point to ceiling point<br><br>5' (1.5 m) to flame touching ceiling | • Interior finish<br>• Fuel arrangement<br>• Feedback<br>• Height of fuels<br>• Proximity of flames to walls<br>• Ceiling height<br>• Room insulation<br>• Size and location of openings<br>• Heating, ventilating, and air conditioning (HVAC) operation |
| 5. Remote burning | Ceiling point to full-room involvement<br><br>Flame touching ceiling to flashover | • Fuel arrangement (amount and location)<br>• Ceiling height<br>• Length/Width ratio<br>• Room insulation<br>• Size and location of openings<br>• HVAC |
| 6. Full-room involvement | Ceiling point to full-room involvement<br><br>Flame touching ceiling to flashover | • Fuel arrangement (amount and location)<br>• Ceiling height<br>• Length/Width ratio<br>• Room insulation<br>• Size and location of openings<br>• HVAC<br>• Fire protection and control features |

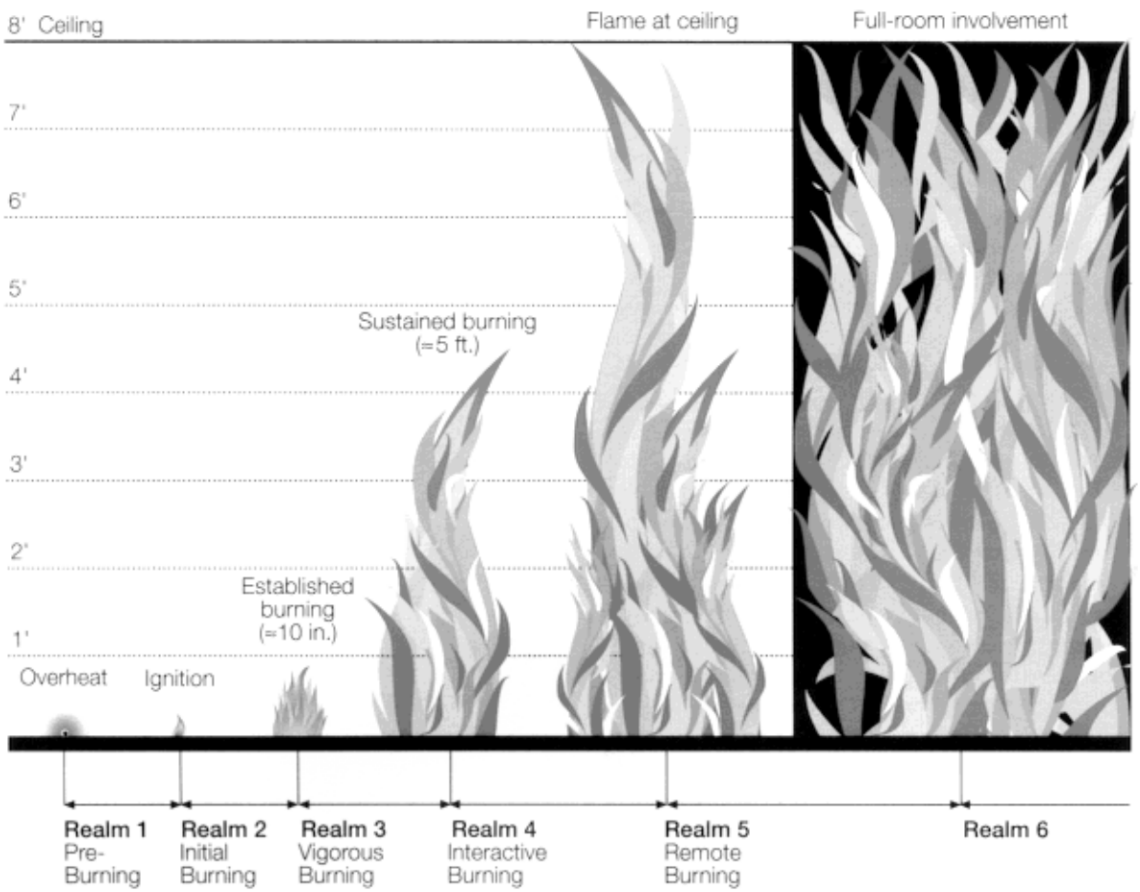



**Figure 2-8**
**Graphic Depiction of the Fire Realms**

Initial fire behavior within a compartment often will determine the extent of fire spread within and beyond the compartment of origin. While the fire prevention goals of preventing ignition from ever occurring are laudable, in code enforcement we must assume that an unwanted ignition will occur at some time. When a fire has reached a point where the size of the flame is sufficient to allow for continued flaming combustion without any additional, independent heat source, it is considered to be "established burning." The flame height during this phase often is considered to be at 10 inches (250 mm) from the fuel surface.

## Fire Plumes

Directly above the fire, a column of hot gases and combustion products rises upward. This column is known as a "plume." As the hot gases rise, cooler air is drawn in or entrained into the plume; this is known as "entrainment." This cooler air is drawn from around the base of the fire and the boundaries between the plume and the surrounding air. (Remember Faraday's candle description.) The temperature of the plume decreases with the height above the fire, due to cooling effects of the entrained air.

As long as the environment around the fire plume is relatively stable and not influenced significantly by ventilation, the fire plume will rise in the shape of a cone. (When this pattern remains on a vertical surface after a fire, investigators often describe it as a V-pattern.) If doors or windows are opened, or a smoke management system operates, the path of the fire plume may vary dramatically. Likewise, if the fuel array within the space is irregular, the fire plume may follow it.

Once the plume temperature equals the surrounding air temperature, fire gases and smoke stop rising because they lose their buoyancy. Buoyancy is upward force due to the molecular activity of the heated gases near the fire plume. When this equalization occurs, the smoke begins to spread out horizontally, or stratify. In a tall compartment, such as an atrium or covered stadium, or with low energy fires, this loss of buoyancy may result in delayed activation of automatic fire detection devices, automatic fire sprinklers, rooftop smoke vents, or smoke management systems. Prescriptive building codes for a long time have required horizontal separations to prevent vertical air currents from carrying heat and toxic gases throughout the upper stories of a building. Normally, except for atrium designs, the model prescriptive building codes prohibit more than two adjacent floors from sharing a common atmosphere. Furthermore, in some tall, one-story buildings, like warehouses, fire-resistive construction may be omitted at the ceiling because there may not be enough thermal energy to threaten the structure at the high elevations.

In day-to-day conditions, often we observe indoor air movement patterns that are influenced by the exterior weather conditions. The "stack effect" is the natural, vertical air movement in buildings caused by temperature differences and densities between indoor and outdoor air. Like fire plumes, when the buoyancy of the natural air currents diminish, the stack effect may cause normal air pollutants in the ambient environment to spread horizontally.

## Ceiling Jets

When the flames reach a ceiling or other horizontal barrier, the smoke and combustion products will spread laterally from the plume centerline. If the ceiling is smooth and flat, the flow generally is equal in all directions. The movement of the smoke and combustion products across the ceiling is known as the "ceiling jet." Plumes and ceiling jets are the mechanisms by which the hot gases and combustion products reach automatic fire detection devices and sprinklers.

Obstructed construction (such as beam pockets, waffle-slab construction, or deep joists), sloped or arched ceilings, irregular shapes, and finish materials affect the speed and direction of ceiling jets.

Figure 2-9 illustrates a fire plume and ceiling jet.

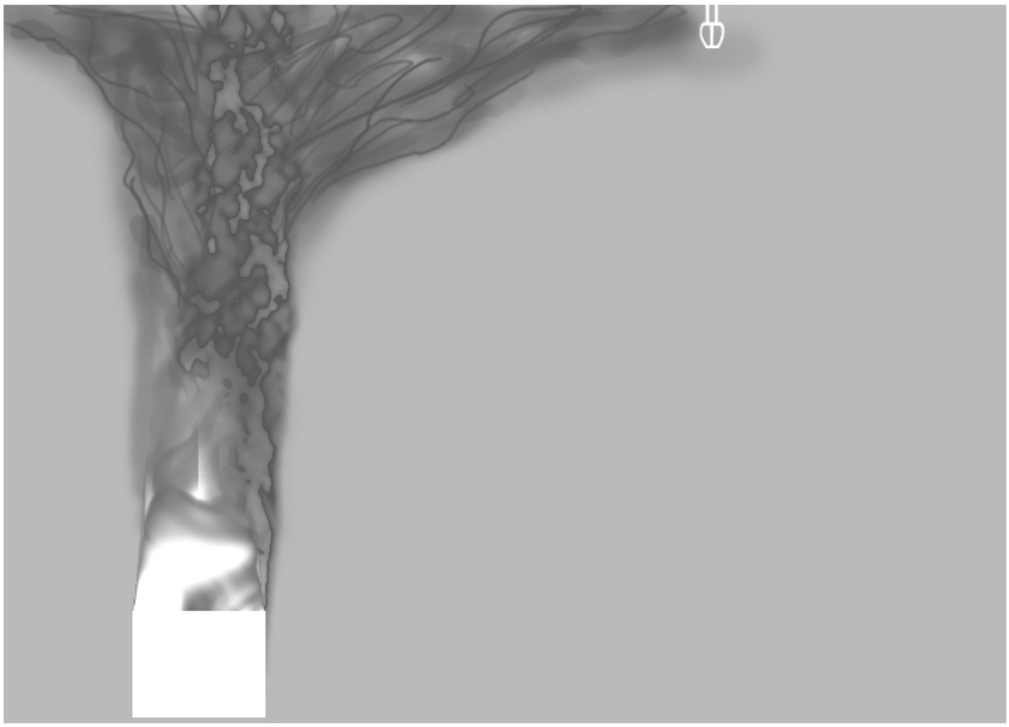


**Figure 2-9**
**A Fire Plume and a Ceiling Jet**

## Flashover

As the fire in a compartment progresses, hot gases and combustion products rise, flames reach the ceiling, spread out (the ceiling jet), and begin to fill the upper portions of the room forming what is known commonly as the "upper layer." Sometimes the upper layer also is referred to as the smoke layer or hot gas layer. As the fire continues, the upper layer thickens and will flow out into adjoining compartments through any openings. As the fire intensifies (increased HRR), the upper layer will descend closer to the floor. This results in what is known as "radiation feedback": the condition of electromagnetic waves reflected from one heated surface to another. In this case, the opaque surface of the upper layer is an excellent reflector to radiate the heat back toward the floor. The temperature in the upper layer also will increase, resulting in greater radiant heat levels on other objects in the compartment.

If sufficient radiant heat is projected on the other objects in the room, flashover will occur. Flashover is the transition phase in the development of a fire: the combustible surfaces exposed to thermal radiation reach ignition temperature nearly simultaneously and fire spreads rapidly throughout the space. Under flashover conditions, the fire is dominated by the burning of all items in the compartment. It is the final realm of a growing fire.

Flashover generally occurs when the upper layer temperature reaches approximately 1,100 °F (593 °C) and the radiant flux (heat flow) from the upper layer reaches approximately 20 $kW/m^2$ (0.00176 $Btu/ft^2/sec$). It has been shown that if the flame can be prevented from reaching the ceiling, the

possibility of flashover occurring is reduced. Once flashover occurs, excess fuel vapors that cannot be consumed or combusted with the air available in the compartment will be produced and the fire will become ventilation controlled.

A ventilation-controlled fire may result in flame extension through vent openings into adjacent compartments and/or windows, if they fail or are open. Flashover will not occur in every fire scenario. If the fuel is limited or ventilation is insufficient, the ceiling layer may not develop sufficiently to make the transition to flashover.

### Flameover or Rollover

It is possible for flameover to occur prior to flashover. Flameover is the condition where the underburned smoke and gases accumulated in the ceiling layer ignite. It is possible for flameover to occur without flashover. This condition also is known as "rollover."

### Fully Developed Fire

A fully developed fire is a steady or postflashover fire at peak HRR. Its peak burning will last for a short or an extended time, depending on available fuel and oxygen. Some fully developed fires occur with total involvement of the fire enclosure, often leading to spread to other enclosures if adequate fuel and oxygen exist and there is no compartmentalization or active fire protection to slow or suppress the fire.

## HEAT TRANSFER: HOW FIRES SPREAD IN THE ENVIRONMENT

In the environment, warm objects release their heat energy to cooler objects until a thermal balance is achieved. This balance is called "homeostasis." As heat is applied to a fuel in the early phases of combustion, some of the heat is absorbed or conducted into the interior of the material by molecular action. Conductivity is the ability of material to conduct heat, and materials with a higher density have a tendency to be more efficient heat conductors. Some construction materials--especially unprotected steel or metal products--are excellent heat conductors.

A material's conductivity can be demonstrated by the following examples:

- Grasp an empty expanded plastic foam coffee cup. Notice that your hand feels warmer. This is because your body heat, which previously had been lost to the atmosphere, now is retained by the insulation effect of the cup and sensed by the nerves in your skin.

- To compare, place your hand on a dense wooden surface like a tabletop. Notice that your hand feels cooler than before. This is because some of the heat from your hand is being absorbed into the table surface that generally is denser that the expanded foam cup.

Denser materials require more molecular energy to raise their temperature. The surface of such a material will heat more slowly, and therefore delay ignition. Many building materials used in fire-resistive construction (i.e., gypsum, concrete masonry units, monolithic concrete, spray-on fireproofing) are effective because of their high heat resistant values.

## Heat Transfer Methods

A major factor affecting fire behavior is heat transfer. This affects ignition, growth, spread, decay, and extinction. Building and fire code requirements often are predicated on the goal of minimizing the influence of heat transfer. The three mechanisms of heat transfer are conduction, convection, and radiation.

### Conduction

Conduction is the form of heat transfer that takes place within or between solids when one portion of an object is heated. For example, if you place your hand on your desk it will feel cold because you are transferring heat from your hand to the desk. Energy is transferred from the heated area to the unheated area. If the thermal conductivity of the material is high, the rate of heat transfer will be high.

In the built environment, the use of steel for construction materials is very common. Steel has a high thermal conductivity and, when heated, may ignite objects far from where the initial fire started.

### Convection

Convection is the transfer of heat energy by the movement of heated liquids or gases from the source of heat to a cooler part of the environment. For example, if you place your hand above a lighted candle, you will receive heat by convection.

Convection plays a major role in the spread of smoke and fire gases to the upper portions of the room of origin and throughout a building. Building codes do a lot to prevent or mitigate the impact of convective heat spread: stair enclosures, shaft protection, horizontal floor/ceiling assemblies, even roof-top smoke and heat vents are important code tools used to control vertical heat transfer.

### Radiation

Radiation is the transfer of heat energy from a hot surface to a cooler surface by electromagnetic waves without an intervening medium. For example, if you put a lighted candle into a holder and hold your hands on either side of it, your hands will be heated by radiation. Radiant energy is transferred only by line of sight and will be reduced or blocked by intervening opaque materials.

Building codes address radiant heat risks in one of two ways: increasing the distance between buildings or increasing the fire-resistive construction requirements of exterior walls.

## Heat Flux

Heat flux is simply the measurement of the amount of heat that is transferred to a surface or target fuel. Heat flux is expressed as the heat flow rate per unit area and is measured in Btu/ft$^2$/sec or kW/m$^2$. Heat flux measurement is important when evaluating the likelihood that a fire will migrate through a structure. It also is used in the Radiant Panel Test (see below) to evaluate the combustibility of floor covering products.

Table 2-12 provides samples of representative heat fluxes.

**Table 2-12**
**Heat Flux Values for Common Conditions**

| Heat Flux Radiated From | Btu/ft$^2$/sec | kW/m$^2$ |
|---|---|---|
| Human body on hot summer day (98 °F, 37 °C) | 0 | 0 |
| Interior through insulated wall (R19) on cold winter day (14 °F, -10 °C) | 0.0008 | 0.009 |
| Human body on cold winter day | 0.22 | 0.025 |
| Sun, on a clear day in the tropics | 0.12 | 1.4 |
| 100-watt incandescent bulb at 3.9 inches (10 cm) | 0.56 | 6.4 |
| Source that burns human skin in 10 seconds | 0.88 | 10 |
| Source that burns human skin in 1 second | 4.41 | 50 |
| Propane torch at flame tip | 8.81 | 100 |
| Oxy-acetylene torch at flame tip | 88 | 1,000 |
| Surface of the sun (radiation only) | 5,727 | 65,000 |

Source: Vatell Corporation.

Table 2-13 provides samples of the minimum heat flux required to ignite these products.

**Table 2-13**
**Minimum Heat Flux for Ignition**

| Material | Btu/ft$^2$/sec | kW/m$^2$ |
|---|---|---|
| Phenolic foams, rigid | 0.616 | 7 |
| Red oak | 0.968 | 11 |
| Polyethylene, rigid | 1.672 | 19 |
| Polyethylene, foam | 1.672 to 1.936 | 19 to 22 |
| Polypropylene | 1.76 | 20 |
| Polystyrene, foams or rigid | 1.584 to 2.376 | 18 to 27 |
| Polyvinyl chloride | 1.848 | 21 |

Source: NFPA *Fire Protection Handbook*, 18th edition.

## Fuel Geometry or Location

The geometry or location of the fuels also can affect overall fire behavior. Large volume compartments or compartments with high ceilings allow dilution of fire gases and provide a "reservoir" for smoke. A fuel package located in a corner will result in faster fire growth than one located against a flat wall or out in the compartment. The number and configuration of compartment walls also can affect overall fire behavior. These factors will influence heat transfer and thus affect overall fire behavior. In some building designs, this "reservoir" concept may be an effective method to consider for managing smoke migration throughout a structure.

Fuel geometry (the placement of fuel in the structure) also is important. Fuels that already are in a liquid or gaseous state are more hazardous than solid fuels because they are ignited more easily and may respond to environmental conditions such as wind or gravity; but even the configuration of solid fuels is important.

Due to radiation feedback, a fire that originates in a small or confined space typically will grow faster than one that originates in the center of a large room. Certain construction materials, such as concrete or masonry floors, walls, and ceilings, are noncombustible and will act as heat "sinks," absorbing heat energy. Combustible materials that usually will ignite include paneling, wallboard, ceiling tiles, wood framing, manufactured wood, and oriented strand board (OSB). The presence of heat sinks and combustible surfaces affects the rate at which a building contents fire becomes a structure fire, and the likelihood it will spread beyond the room of origin.

Fuel placement of things such as furniture, storage, and finishes within a building influences the development of a fire. How fuel burns depends on ventilation, surface area, and radiation feedback between the combustible materials and the room, walls, and ceiling surfaces. Some of the most dramatic examples of the impact of fuel placement come from applied research performed by FM Global Research (formerly Factory Mutual Research). Their warehouse fire protection study videos clearly show how materials stored on closely arrayed racks or pallets burn more ferociously than similar products separated by wide aisles and stored less than 12 feet (4.2 m) above the floor.

The size of the fuel also influences the fire development; as does the density--the thermal thickness or thinness--of the fuel. For example, a thick board will not burn so quickly as thin paneling; and a flat wall will burn less readily than a corner section (all things being equal, especially finishes).

All of these factors can influence the ignition potential, ventilation, available fuel, surface area, and heat transfer mechanisms during a fire event.

## Interior Finish Flammability

Even if a building is constructed of noncombustible materials, human occupants still introduce combustible finishes to soften the environment. Many tragic fires have occurred from easily- ignited or fast-burning interior finishes on walls or ceilings.

## Walls and Ceilings

To identify and categorize materials to their relative fire risk, building codes classify interior wall and ceiling materials by flame spread ratings in accordance with Steiner Tunnel Test requirements (ASTM E84 and NFPA 255 standards). Materials are classified to indicate their ability to support combustion and flame, as well as the amount of smoke generated by the burning sample. Finish materials are compared to the fire spread characteristics of red oak to express their relative risk.

Almost all building codes cite ASTM E84 as the basis for their applied standards. This test, widely known as the Steiner Tunnel Test, simulates a fire exposure of about 2,400 °F (1,315 °C) in the area of the flame. In the test, a 36 sq. ft. (3.34 $m^2$) test sample is placed in the top of the Steiner Tunnel, and heated by gas flames for 10 minutes at a rate of about 5,000 Btu/min (88kW). This creates a temperature near the test sample of about 1,600 °F (871 °C).

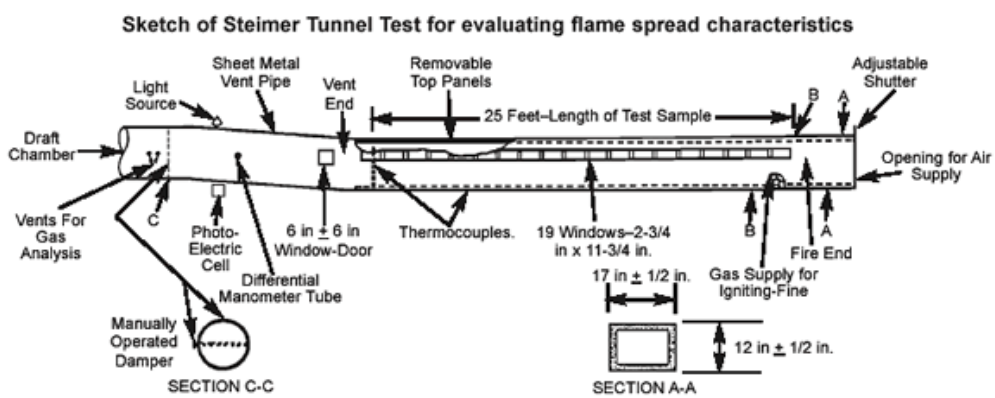



**Figure 2-10**
**Steiner Tunnel Test Apparatus**

The time is measured for the flame to travel down the tunnel for the length of the material, or until the flame ceases. That time is then imposed on a dimensionless scale developed by rating cement asbestos board time performance at "0," and the time performance of select grade red oak at "100." These ratings indicate the rate at which fire will spread across the surface of a material. For example, a wall decorated with paper will have a faster flame spread rating than a bare wall.

Table 2-14 represents the classifications from the Steiner Tunnel Tests. The numbers in the Flame Spread Rating column are derived from mathematical formulas, and are **not** interpreted as feet/sec, inches/min, etc.

**Table 2-14**
**Flame Spread Classifications**

| Class | Flame Spread Rating | Max. Smoke Development |
|---|---|---|
| 1 or A | 0 to 25 | 450 |
| 2 or B | 26 to 75 | 450 |
| 3 or C | 76 to 200 | 450 |

Likewise, the maximum smoke development values are derived mathematically from a light absorption per minute relationship. NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials*, provides a detailed explanation of the Steiner Tunnel Test procedures.

## Floor Finishes

Floor surfaces, because of their orientation and radiation feedback from heated upper layers of a fire, respond differently from walls or ceiling finishes. Consequently, they must be tested under different conditions.

Floor covering samples are tested in accordance with ASTM E648 and NFPA 253, *Standard Method of Test for Critical Radiant Flux of Floor Covering Systems Using a Radiant Heat Energy Source*, that measure "critical radiant flux," the amount of energy from an overhead test apparatus that will ignite the floor finish. The test is intended to simulate the conditions from a room flashover.

The building and fire codes establish floor finish "classes" based on the materials' ignition resistance. Class 1 indicates a higher amount of heat is required ($0.45 W/cm^2$). Class 2 indicates a lower amount of heat is required ($0.22 W/cm^2$). From a fire safety perspective, Class 1 is preferable to Class 2.

Fire officials must remember that, before approving a product for installation, the test data must represent the conditions in which the material will be used. For example, carpeting that will be installed on a wall must be tested in accordance with the flame spread requirements established in the Steiner Tunnel Test rather than the critical radiant flux procedures.

## Structures and Contents

The geometry of structures and contents has a significant effect on the outcome of a fire. Codes recognize this by establishing property line setbacks, minimizing vertical openings, separating or isolating hazardous processes or occupancies, and providing active fire protection to detect, confine, and control a fire.

### Building Design Influences

We construct buildings to protect people and possessions from the elements including rain, snow, sleet, floods, earthquakes, cold, heat, dust, and even outdoor fires. When we erect structures, we create spaces that define boundaries. The walls, floors, and roofs of buildings provide an "envelope" in which myriad human activities occur. Unfortunately, one of these activities can be unwanted fires.

Students of fire protection history know how major fires and catastrophes influence changes in building and fire codes (see Unit 1: Fire in America). We anticipate that these changes will result in better structures that are able to resist these environmental influences. But what about the buildings' interiors? What designs, orientations, architectural statements, or materials influence fire behavior? Not every building shares the same geometric features of slab floor, plumb walls, flat ceilings, or limited openings. The wide variety of spatial designs affect fire plumes, ceiling jets, heat transfer, and smoke migration. These design considerations also include the location of the structure on the site and its proximity to other buildings or fire hazards, e.g., structures, fuel tanks, and the proximity of the fire to walls and corners, all of which also affect fire behavior.

In the prescriptive building codes, passive fire-rated separations (i.e., firewalls and floor/ceiling assemblies) and fire sprinkler systems are required to provide a means to slow a fire for occupant escape, or to keep a fire small enough that the fire suppression forces should be capable of controlling it. In performance-based designs, these separations may not be employed when considering the other features that may be provided.

Some of the building design influences that affect fire behavior include

- **Compartment volume**. Small compartments generally will reach flashover conditions faster than large ones because of the reradiative effects of the smoke layer and the proximity to adjacent combustibles.

- **Ceiling height**. All things being equal, it seems obvious that the higher the ceiling is above the fire, the longer it takes for the fire plume to reach it. But what about conditions where the ceiling height is variable in the same compartment? How can fire behavior be predicted consistently in the variable environment?

- **Ceiling configuration**. There are almost unlimited challenges created by heavy timber or concrete waffle-deck construction where deep pockets affect air currents, creating eddy effects in fire plumes and ceiling jets.

- **Ceiling slope**. The design and geometrics of sloped ceilings are limited only by an architect's creativity and an engineer's ability to provide structural support. One must consider the differences in fire plumes and ceiling jets among arched, sloped, clerestory, or dome ceiling designs.

- **Atriums**. A popular design feature used to provide interior spaciousness, atriums penetrate more than two adjacent floors of a building, thus creating a chimney effect for hot smoke and toxic gases. Air flow through and from adjacent tenant spaces may affect air distribution currents. Many atriums are outfitted with sprinklers and smoke management systems that will affect fire behavior.

  In some circumstances, the height of the atrium is significant enough to observe stack effect in the atrium: the condition where heated fire gases lose their upward buoyancy and begin to settle out or travel horizontally.

- **Vertical and horizontal openings**. Prescriptive building and fire codes focus heavily on confining fires both vertically (floor/ceiling assemblies, stair enclosures, shaft construction) and horizontally (fire separations, firewalls) within the limits established by the codes.

  Furthermore, the prescriptive codes pay close attention to those spots where penetrations occur through fire-resistive barriers. Pipes, tubes, cables, and related features that are "punched through" fire-resistive walls and ceilings are a weak spot in the barrier, and must be protected to an equivalent level of fire resistance.

- **Surface finishes**. The interior finish of the space must be evaluated carefully. Material flame spread ratings must be considered, especially if the proposed design incorporates a new material, or an old material applied in a new way.

- **Construction materials**. Different materials may behave differently under similar environmental conditions. A concrete masonry unit (CMU) wall may be constructed as a firewall and provide substantial fire resistance based on its hourly rating. A wood-framed, gypsum wallboard-covered wall may have a similar fire-resistance rating, but once compromised may not survive.

- **Active fire protection**. Sprinklers, water spray, smoke management, and special agent systems all play an important part in fire control. The code official must ensure that these items are considered when reviewing the potential fire behavior in a structure.

- **Ventilation**. Natural or mechanical ventilation, or both, dramatically affect fire behavior in buildings. How might "normal" air currents change when the HVAC system operates? Or, what will occur when the HVAC system--which may be an integral part of the smoke management system--fails to operate?

## Influences of Contents

Building contents may change daily. One day, a structure may have a nominal amount of combustibles in it, and the next, it may be full of highly flammable materials.

Some of the contents influences that the code official must consider when assessing hazards include

- **Fuels**. For years, the fire service has referenced Class A combustibles: those products that leave an ash when they burn. The fire behavior of most Class A combustibles is compared to that of ordinary wood products having a heat of combustion of about 8,000 to 10,000 Btu/lb (18,608 to 23,260 kJ/kg), and usually easily extinguished with adequate quantities of water.

  Now, however, fuels come in a variety of materials: rigid and foamed plastics, flammable and combustible liquids, mixed plastics and ordinary combustibles, animal and vegetable products, metals and wood, plastics and wood, and polymers. Add to this the vast selection of packaging and shipping materials and the fire protection challenge is enormously complicated.

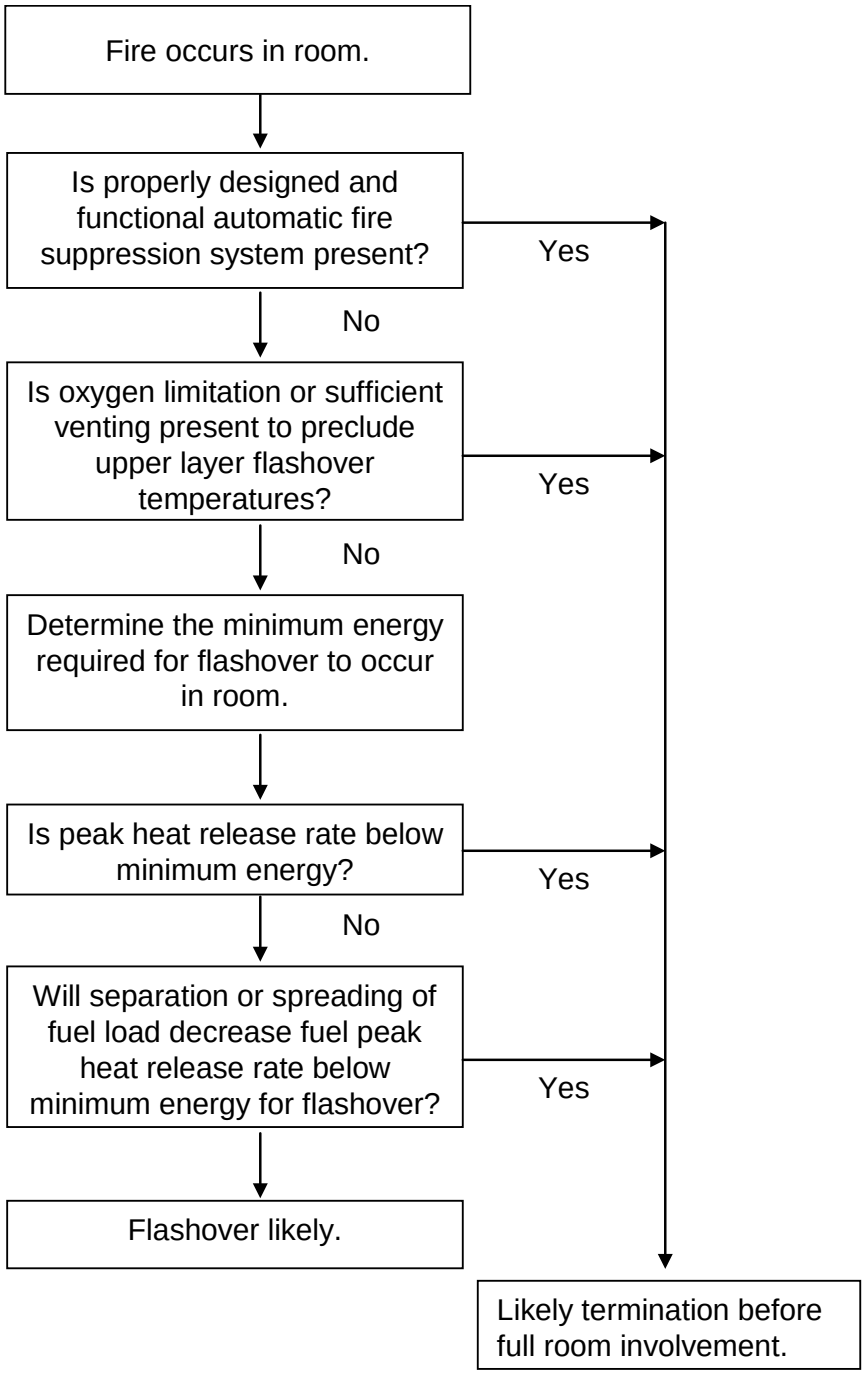
  As an example, under the prescriptive requirements of NFPA 13, *Standard for the Installation of Sprinkler Systems*, in storage occupancies contents are categorized into "commodity classes." The commodity class that is assigned (I to IV, with IV being the most hazardous of the list) establishes fire sprinkler system requirements for discharge density and area of application. Generally, it is most cost effective to install fire protection for the commodity class that most likely will occur in the facility. Thus, if a storage facility operator stores only books in cardboard boxes, the fire protection system likely would be designed to protect a Class III commodity. If the commodity were changed to Class IV, the fire sprinkler system may not be adequate to protect the new risk.

- **Storage arrays**. The location and method of contents and storage in a building also affects the successful outcome of a fire. Ordinarily, wide aisles with lots of space between displayed goods, furniture, or other contents are the best means of preventing fire from spreading from one storage area to another.

  When combustibles are stored on racks, shelves, pallets, or in other configurations, the fire protection challenge increases. FM Global Research has performed years of study on the issues of these so-called "high challenge" fires. The code official must know exactly how materials will be stored or handled in a building to evaluate the adequacy of the performance design.

## National Fire Protection Association Standard 555

NFPA 555, *Guide on Methods for Evaluating Potential for Room Flashover*, provides designers and the code official a seven-step flowchart to assess the likelihood that flashover will occur within the room of fire origin. While much of the guide is based on sophisticated scientific principles and measurements, the flowchart focuses decisionmaking into those factors that may affect an incipient fire's outcome.




Source: NFPA 555, *Guide on Methods for Evaluating Potential for Room Flashover*, 2000 edition.

**Figure 2-11**
**Flowchart for Evaluating Potential Room Flashover Toxicity**

Fire officials and health care practitioners have known for a long time that, despite the public's perception about fires, smoke and toxic gases really are the predominant killers.

During combustion, fuels may release toxic constituents, or chemical reactions that occur during the fire may create toxic materials. These materials may include gases or particulates, including carbon monoxide, carbon dioxide, hydrogen cyanide, formaldehyde, hydrogen fluoride, soot, nitric oxide, and nitrogen dioxide. Table 2-15 below provides a list of some toxic materials that result from combustion of various products.

**Table 2-15**
**Toxic Materials as a Result of Combustion**

| Material | Toxic Gas or Vapor |
|---|---|
| All combustible materials containing carbon | Carbon dioxide, carbon monoxide |
| Celluloid | Nitrogen oxides |
| Leather, plastics containing nitrogen, cellulose materials, cellulosic plastics, and rayon | Hydrogen cyanide |
| Rubber, thiokols | Acrolein |
| Fire-retardant plastics, fluorinated plastics | Sulphur dioxide |
| Melamine, nylon, urea formaldehyde resins | Halogen acids (hydrochloric hydrobromic, hydrofluoric acids, phosgene) |
| Phenol formaldehyde resin | Ammonia |
| Phenol formaldehydes, wood nylon, polyester resins | Aldehydes |
| Polystyrene | Benzene |
| Foamed plastics | Azo-bis-succino-nitrile |
| Some fire-retardant plastics | Antimony compounds |
| Polyurethane foams | Isocyanates |

## Toxic Fire Gases

Even incomplete combustion causes problems. Carbon monoxide is one of the leading causes of fire deaths because of its affinity for the oxygen-carrying red blood cells in humans. Carbon monoxide quickly attaches to the red blood cells, blocking out their oxygen-carrying capacity and creating a potentially lethal condition where oxygen is unable to get to the brain and sustain life. Even if a person is not killed outright, the effects of carbon monoxide poisoning include disorientation and impairment.

Smoke, another constituent of incomplete combustion, reduces visibility and increases occupant anxiety. Increasing smoke conditions may prevent occupants from seeing exits or exit signs. Choking smoke may keep people from leaving to find clearer areas.

The subject of toxicity and smoke is a specialized and highly technical topic that will not be covered here. The important matter for the code official to remember is that any performance-based proposal must address the issues of smoke management, human behavior, and egress.

## SUMMARY

While in a perfect world there would be no unwanted fires, and no need for building and fire codes, we do not live in a perfect world. An understanding of the dynamics of fire behavior will enable the code official and the designer to use building design strategies to control fire development and spread.

Design strategies that promote fire safety include

- limiting or removing sources of ignition;
- separation of fuel and ignition sources; and
- using materials with good fire performance.

# Activity 2.2

# Fire Dynamics Terminology

## Purpose

To assess your comprehension of key terms related to fire dynamics and fire behavior.

## Directions

1. You will have 30 minutes to complete this "closed book" quiz.
2. On the following worksheet, match the number next to the term to the correct definition.
3. Be prepared to discuss your answers at the end of the quiz.

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## Activity 2.2 (cont'd)

### Worksheet

| Term | Term | Term |
|---|---|---|
| 1. Flashpoint | 11. Flashover | 21. Homeostasis |
| 2. Boiling point | 12. $T^2$ fire | 22. Flameover |
| 3. Conduction | 13. Heat flux/transfer | 23. Basic research |
| 4. Heat-release rate | 14. Ceiling jet | 24. Closed system |
| 5. Convection | 15. Backdraft | 25. Boyle's Law |
| 6. Flammable limits | 16. Fire plume | |
| 7. Oxidizer | 17. Standard Time/Temperature Curve | |
| 8. Heat of combustion | 18. Cone calorimeter | |
| 9. Radiation | 19. Stack effect | |
| 10. Triple point | 20. Pyrolyzate | |

| Answer | Definition |
|---|---|
| | The transfer of heat energy by the movement of heated liquids or gases from the source of heat to a cooler part of the environment. |
| | The temperature at 1 atm where the liquid's vapor pressure equals the atmospheric pressure. |
| | The transfer of heat energy from a hot surface to a cooler surface by electromagnetic waves without an intervening medium. |
| | A material that yields oxygen or other oxidizing gas, or that reacts to promote or initiate combustion of combustible materials. |
| | The temperature at which a liquid emits adequate vapors that will ignite with a spark, but not sustain combustion. |
| | The upper and lower concentration limits of a vapor or gas in air that can be ignited. |
| | The rate at which a fuel burns and releases its energy. |
| | The total Btu (calorie) value that can be extracted from a fuel under perfect conditions. |
| | The condition where the underburned smoke and gases accumulated in the ceiling layer ignite. |
| | The temperature and pressure at which three phases (gas, liquid, and solid) of that substance may coexist in thermodynamic equilibrium. |

| | |
|---|---|
| | The measurement of the amount of heat that is transferred to a surface or target fuel. |
| | Vapors and solid particulate matter being released from the fuel during the pre-combustion phase. |
| | The movement of smoke and combustion products across the ceiling. |
| | A column of upward rising hot gases and combustion products. |
| | A test protocol for evaluating the performance of fire-resistive assemblies. |
| | A condition that may occur when oxygen is introduced into a heated, confined space that is oxygen-deficient. |
| | The transition phase in the development of a fire where the combustible surfaces exposed to thermal radiation reach ignition temperature nearly simultaneously and fire spreads rapidly throughout the space. |
| | A test apparatus used to measure total heat output values from a combustible object. |
| | The natural, vertical air movement in buildings caused by temperature differences and densities between indoor and outdoor air. |
| | The form of heat transfer that takes place within or between solids when one portion of an object is heated. |
| | A condition where warm objects release their heat energy to cooler objects until a thermal balance is achieved. |
| | An environment isolated from the effects of the outside world, with matter and energy remaining constant within it, and the effects of gravity and other energy and matter are "shut out." |
| | The principle that, at a constant temperature, the volume of a fixed amount of gas is inversely proportional to pressure. |
| | Efforts to explain the phenomenon of ignition, and the sequence of events that occurs during combustion and fire growth. |
| | The principle that most fires grow exponentially, that is the rate of heat release increases to the square of the burning time. |

# Activity 2.3

## Understanding Fire Dynamics

### Purpose

To identify influences of building design and content arrangement on fire dynamics.

### Directions

1. We will display 10 photographs. Each photograph shows different methods of construction, design, or contents arrangement that may affect fire dynamics.

2. Look at the photographs and answer the questions on the following SAW beside each photograph's number.

3. The instructor will call on volunteers for their answers.

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## Activity 2.3 (cont'd)

## Worksheet

| Photograph | Questions |
|---|---|
| 1 | Identify two methods of heat transfer from a first floor fire that could have an effect on the second floor and roof. |
| 2 | Identify at least one design feature in this room that may affect fire and smoke spread, and one likely method of heat transfer between and among the seats. |
| 3 | What is identifiable in this photograph that might affect fire behavior in this occupancy? |
| 4 | Explain how the design and construction of this floor/ceiling assembly may affect the behavior of fire plumes and ceiling jets. |
| 5 | List at least two items in this photograph that may affect the heat release rate of a fire in this building. |
| 6 | Identify two factors that may influence fire spread in this storage array, and, how the geometry of the array might result in different fire outcomes from the same fuel load were stacked not more than 6 feet above the floor. |

7 Identify at least two construction features of this multiple-family dwelling property that may influence vertical and horizontal fire spread.

_____

_____

8 Identify at least three conditions that may affect the rate of heat release of a fire occurring in this property.

_____

_____

9 Explain how the various physical states of combustibles in this occupancy affect heat release rate and quantity of heat released.

_____

_____

10 Identify at least three features at this facility that affect heat release rate, heat transfer and quantity of heat released.

_____

_____

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# APPENDIX

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## Job Aid 2.1

## Conversion Table*

Most of the test data or model prediction results that may be generated as part of a performance-based fire safety design will be in International System (SI) units. Therefore it is important for the code official to have an understanding of the units that may be used.

With the exception of the kilogram (kg), the conversions given in the table below are to base units such as a Joule (J) or a Watt (W). In the scope of a fire within a building, these units are small, so the values would be reported as kiloJoules (kJ) or kiloWatts (kW). The kilo prefix means multiply the base unit by 1,000. Another prefix that may be used is **mega**. This prefix means multiply the base unit by 1,000,000.

For additional conversion information, you can go to www.convert-me.com/en

| Property | To Convert from | To | Multiply by |
|---|---|---|---|
| Length | Foot (ft) | Meter (m) | 0.3048 |
| Mass | Pound (lb) | Kilogram (kg) | 0.4536 |
| | | | |
| Area | Square foot ($ft^2$) | Square meter ($m^2$) | 0.0929 |
| Volume | Cubic foot ($ft^3$) | Cubic meter ($m^3$) | 0.0283 |
| Energy, work, quantity of heat | British thermal unit (Btu) | Joule (J) | 1055.0 |
| | Btu/lb | Joule/kilogram | 2326 |
| Power, heat release rate | British thermal unit per minute (Btu/min) | Watt (W)=J/s | 17.573 |
| Heat flux | British thermal unit per square foot per minute (Btu/($ft^2$/min)) | Watts per square meter (W/$m^2$) | 189.15 |
| Temperature | Celsius (°C) | Fahrenheit (°F) | (1.8x°C)+32 |
| | | | |
| | Celsius (°C) | Kelvin (K) | (°C)+273.15 |

*NIST Special Publication 811, *Guide for the Use of the International System of Units (SI)*. Gaithersburg: Author, April 1995.

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## Job Aid 2.2

## Sample Peak Heat Release Rates

| Item | Weight (lbs) | Peak HRR (Btu) | Peak HRR (kW) |
|---|---|---|---|
| Burning cigarette | | 0.004739 | 0.005 |
| Burning match | | 0.075828 | 0.08 |
| Small trash can fire | 1.5 to 3 | 47.3 to 284.3 | 50 to 300 |
| Trash bags, 11 gallon with mixed plastic and paper trash | 2.5 to 7.5 | 132.7 to 331.7 | 140 to 350 |
| Cotton mattress | 26 to 29 | 37.9 to 919.4 | 40 to 970 |
| Televisions sets | 69 to 72 | 113.7 to 274.8 | 120 to 290 |
| Plastic trash bags with paper trash | 2.6 to 31 | 113.7 to 331.7 | 120-350 |
| PVC waiting room chair, metal frame | 34 | 255.9 | 270 |
| Cotton easy chair | 39 to 70 | 274.8 to 350.7 | 290 to 370 |
| Gasoline/Kerosene in 2 $ft^2$ pool | | 379.1 | 400 |
| Christmas trees, dry | 14 to 16 | 473.9 to 616.1 | 500 to 650 |
| Polyurethane mattress | 7 to 31 | 767.7 to 2492.8 | 810 to 2630 |
| Polyurethane easy chair | 27 to 61 | 1279.6 to 1886.2 | 1350 to 1990 |
| Burning upholstered chair | | 2369.6 | 2500 |
| Polyurethane sofa | | 2957.3 | 3120 |
| Burning Christmas tree | | 1516.5 to 4928.8 | 1600 to 5200 |
| Base Design Fire* | | 5000 | 5275 |

* Minimum HRR design fire for smoke management system design required by Section 909.9 of the *International Building Code* (IBC).

Source: NFPA 921, *Guide for Fire and Explosion Investigations.*

Conversions

| | | |
|---|---|---|
| 1 Btu per second | = | 1.055 kW |
| 1 kW | = | 0.94786 Btu per second |
| 1 kW | = | 1,000 W |
| 1 MW | = | 1,000,000 W |
| 1 GW | = | 1,000,000,000 W |

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# *UNIT 3:*
# *FIRE-RELATED HUMAN BEHAVIOR*

***OBJECTIVES***

*The students will be able to:*

1. *Describe basic fire-related human behavior in the built environment.*
2. *Explain how the use or occupancy classification affects overall fire and life safety protection features.*
3. *Compare four strategies for preserving life in structures during fires or other environmental emergencies.*

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## INTRODUCTION

While the behavior of fire can be predicted reliably using basic principles of chemistry and physics, a fire event can become unstable when the human (Hu) element is added. The initiation, development, and ultimate outcome of a significant number of fire events is related directly to the actions or inactions of the individuals associated with the incident. Current research indicates that many factors can affect an individual's or group's behavior before, during, and after a fire. These factors include, in no particular order:

- role assumed;
- previous experience;
- education;
- gender;
- perceived threat;
- means of egress;
- actions of others;
- characteristics of the individual;
- characteristics of the physical setting;
- characteristics of the fire or explosion event; and
- response to cues and decision to act.

Not until the early 1970s did the study of fire-related human behavior begin to be recognized as a distinct field of study. Dr. John Bryan, a fire researcher and former professor of fire protection engineering at the University of Maryland, has, over the years, published numerous articles and papers on his research into fire-related human behavior. Dr. Bryan has summarized much of his work, as well as that of other researchers, in *The SFPE Handbook of Fire Protection Engineering*, "Behavioral Response to Fire and Smoke."

## INDIVIDUAL AND GROUP FACTORS

Physiological characteristics of an individual that can affect their fire-related behavior include physical limitations, cognitive comprehension limitations, and knowledge of their physical settings.

### Physical Limitations

Physical limitations may affect an individual's ability not only to recognize a hazard, but to react appropriately. Physical limitations include age (mobility), physical disabilities, intoxication, incapacitating or limiting injuries, or medical conditions. The very old and very young are the most affected by such physical limitations.

## Cognitive Comprehension Limitations

These limitations include age (mental comprehension), level of rest, alcohol use, drug use (legal or illegal), developmental disabilities, mental illness, and the inhalation of smoke and toxic fire gases. Such characteristics often result in delayed or inappropriate response.

## Familiarity with Physical Setting

A person would be expected to assess a hazard posed by a hostile fire event more accurately in a familiar physical environment, as opposed to an event occurring in unfamiliar surroundings (for example, in one's own home as opposed to a hotel or a large place of assembly). It should be remembered that physical or cognitive limitations might minimize or negate the advantages of the physical setting.

## Group Factors

An individual's reaction under emergency conditions also can be affected by group behavior. A group's size, structure, permanence, as well as its roles and norms can have an effect. Research and experience has shown that when individuals are members of a group, they are less likely to recognize and respond appropriately to the sensory clues generated by a hostile fire. The larger the group the more effect group behavior has on the individual.

Data indicate that, in a group environment, individuals will delay their responses to sensory clues until others in the group also acknowledge the clues and react. Research suggests that this reaction is the result of responsibility for action being diffused among the group.

## Group Structure (Role Relationship)

When a group has a defined and recognized leader(s) or similar authority figure, the group tends to react to an incident in a more timely and orderly manner. This does not, however, mean that the reaction is always appropriate. Examples of such environments can include schools, hospitals, nursing homes, and religious facilities.

Interaction among individual members within such groups tends to result in a sense of responsibility for the group as a whole. Because of this, an individual may be more likely to warn others of the threat as opposed to interacting with a group of strangers. In addition, when the group does become aware of the hostile conditions, its organization will, more than likely, result in a more orderly response.

## Group Permanence

This refers to how well-established a group is, or how long a particular group of individuals has been interacting. More established groups such as families, sports teams, or clubs are more formalized and thus will react differently than will a new or transient group such as in a shopping mall or large place of assembly. The latter type of group is more likely to display a variety of conflicting individual behaviors, as each individual responds or reacts on his or her own accord.

## Roles and Norms

A predominant factor within a group during a hostile fire event is gender roles. Research has shown that women are more likely to report a fire immediately, while males may delay notification opting instead to engage in attempts to suppress the fire.

## Actions of Others

*The following is excerpted from a National Fire Protection Association (NFPA) article by Dr. John L. Bryan.*

> The recognition of ambiguous threat cues as signaling an emergency condition may be inhibited by the presence of other people. Experimental studies of the inhibition of adaptive reaction to emergencies (Latane and Darley 1968) created an experimental situation involving college students. While the students were completing a written questionnaire, the experimenter would introduce smoke into the room through a small vent in the wall. If the student left the room and reported the smoke, the experiment was terminated. If the student had not reported the presence of smoke within a six-minute interval from the time smoke was first noticed, the experiment was considered completed. Students alone in the room reported the smoke in 75 percent of the cases. When two passive non-committal persons joined each student, only 10 percent of the groups reported the smoke. When the total experimental group consisted of three naive subjects, in only 38 percent of the groups did one individual report the smoke. Of the 24 persons involved in the eight naive subject groups, only one person reported the smoke within the first four minutes of the experiment. In the single subject situations, 55 percent of the subjects had reported the smoke within two minutes and 75 percent in four minutes.
>
> It was reported in the study that noticing the smoke was apparently delayed by the presence of other persons, with the median being five seconds for single subjects but 20 seconds in both of the group conditions. These results undoubtedly reflect the constraints that people accept regarding their behavior in public places. The performance of naive subjects in the passive confederate situation was reported as follows:

"The other nine stayed in the waiting room as it filled up with smoke, doggedly working on their questionnaires, and waving the fumes away from their faces. They coughed, rubbed their eyes, and opened the window, but did not report the smoke."

It has been suggested that while trying to interpret the emergency potential of ambiguous threat cues, the individual is influenced by the behavioral reaction of others. Should these others remain passive and seem to interpret the situation as a nonemergency, the individual will tend to have this interpretation modified by this inhibiting social influence (Latane and Darley 1968). This behavioral experiment may help explain the reported tendency of people to (1) disregard threat cues, or (2) interpret them as being nonthreatening when the threat situation occurs where there are many other people such as in a restaurant, motion picture theater, or department store. These experimental results may be of assistance in explaining the incidence of calls received by fire departments minutes or even hours after the incident was first detected. In the report of the Arundel Park Hall fire (Bryan 1957), several of the sample population indicated that when they entered the hall after observing the fire from outside the building, they warned their friends and suggested they should leave, but were laughed at and their warning apparently disregarded.

## PHYSICAL SETTING

### Characteristics of the Physical Setting

The character of the physical setting in which a hostile fire event occurs not only can affect the behavior of the fire itself, but also can affect fire-related human behavior. Physical factors of the setting include locations of exits, number of exits, height of structure, fire alarm systems, fire-suppression systems, and special hazards.

### Locations of Exits

If the location of available exits is not known to the occupants or not identified clearly, confusion and heightened levels of anxiety may result. Clear, unobstructed means of egress reduces the perception of threat.

Special consideration must be provided for occupants who, because of age, are unable to evacuate. The very young and elderly are not as likely to be able to manage the threat of fire.

The very young--usually under age six--are usually very mobile, but have great difficulty in using steps and in following the predetermined path of travel. Unless special education has been provided they do not understand **EXIT** signs, and must be directed for movement; doors and door latches are barriers.

Those over age 60 may replicate characteristic behavior of the very young. Possible compensations for both age groups include direct exit to the exterior, and ramps in lieu of steps.

Handicapped and infirm individuals sometimes are unable to use most common methods of escape. Assigned assistants and special provisions for movement on stairs are valid considerations. It is recommended that areas of refuge and handicapped closets with special equipment be established in highrise occupancies and educational facilities. By designating special emergency procedures arriving suppression forces are enhanced in their efforts to provide for those of limited mobility.

Restrained individuals (jails, detention, psychiatric institutions) also require special emergency procedures.

## Number of Exits

An inadequate number of exits, blocked or restricted exits, or unprotected exits may result in occupants being exposed to the hostile fire and its byproducts.

## Height of the Structure

Some individuals believe that they are less safe in taller buildings in fires. This may result in their failure to follow directions given via voice alarms or other means.

## Reactions to Special Hazards

Plant/Industrial fire safety--often protection is provided by specially trained plant personnel such as a fire brigade or haz mat responders.

Flammable material, unstable material, and manufacturing or transportation of flammable, hazardous materials require special procedures and staff reaction during a fire/spill incident.

## Fire Alarm Systems

Fire alarm systems are among the many factors of built-in protection that can be critical to an individual's ability to become aware of a hostile fire. Research has documented that verbal, directive messages may be much more effective in creating an appropriate response than standard audible alarm appliances.

Proper design and maintenance of such systems also is important, since a history of false alarms and/or malfunctions reduce the overall effectiveness of the system. This is the "cry wolf" syndrome, which may lead to individuals not responding appropriately to actual alarm conditions.

### Fire-Suppression Systems

The presence of fire-suppression systems can have both positive and potentially negative effects. The positive and overwhelming effect is that such systems provide an increased margin of safety, controlling or suppressing the fire, sounding an alarm, and providing more time for the occupants to react appropriately. One negative effect is the possible decrease in visibility that can be the result of application of a suppression agent.

## FIRE CHARACTERISTICS

### Basic Fire Characteristics

The characteristics of the fire are related directly to the individual's or group's perception of the hazard or threat they face. These characteristics include the presence of flames, smoke, the effects of toxic gases, and oxygen depletion.

### Presence of Flames

Because many individuals have uneducated or misinformed perceptions of the hazards of a structural fire, the hazards or threats presented to them may be underestimated. This is particularly true related to the observation of the presence of flames. While the sight of flames makes it clear that a fire is underway and that some level of danger is present, the lack of understanding of fire dynamics and how quickly a fire may grow and spread, may lead some to underestimate the true danger.

### Presence of Smoke

The lack of understanding of fire dynamics also may result in misinterpretations of the hazards presented by smoke. Individuals may perceive heavy, dark smoke as an immediate threat, but may see light, gray smoke as not presenting an immediate threat.

### Effects of Toxic Gases and Oxygen Depletion

Quite often during a fire, individuals inhale the byproducts of combustion, including toxic gases present in the smoke. The development and progression of the fire, in addition to the presence of these fire gases, often results in a depletion of the available oxygen level. Toxic gas inhalation and/or oxygen concentrations below approximately 15 percent can affect an individual's behavior and result in perceptual and behavioral changes. These changes may result in delayed or inappropriate responses and decreases in strength, stamina, mental acuity, and perceptual ability.

The primary fire gas, carbon monoxide, acts as an intoxicant and directly affects the body's ability to absorb oxygen. Other fire gases are irritants that cause burning and tearing of the eyes and burning of the lungs and breathing passages.

## CUES AND DECISIONS

### Response to Cues and Decision to Act

In any fire situation, the individual's ability to recognize and respond to the hazard directly affects his or her ability to survive. The individual must perceive the danger, make a decision about what action to take, and carry out that action.

Panic is a rare event that occurs under specific conditions, primarily when the individual believes that he/she no longer can escape safely. Most important individual decisions and behaviors occur prior to the arrival of the fire department. The way in which an individual is alerted determines the degree of threat perceived.

### Perception of the Danger (Sensory Clues)

Individuals can become aware of a hostile fire situation by one or a combination of several sensory clues. This perception can be affected by several factors, such as whether the person is awake, asleep, or impaired. Impairment can be physical, mental, or the result of the effects of various chemical agents including fire gases, alcohol, or drugs.

Sensory clues include sight or the direct view of flames, smoke, visual alarms or flicker; sound, including crackling, failure of windows, audible alarms, dogs barking, children crying, voices, or shouts; feel, which includes temperature rise or structural failure; and smell of smoke odor.

### Decision to Act

Once an individual perceives that a danger exists, a decision must be made as to how to respond. This decision is affected directly by the person's perception of the degree of danger. Additionally, an individual's degree of impairment is also a factor. Actions that can be taken include ignore the problem, investigate, fight the fire, give alarm, rescue or aid others, reenter after successful escape, flee (escape), or remain in place.

### Experience and Training

#### Previous Experience

Previous experience affects ability to size up and compare the present experience with any previous fire experience. This is a dynamic process, which alters choices.

## Education

An individual's emotional reaction to a fire will be influenced largely by familiarity with the extinguisher, experience in using it or observing its use, training and self-confidence, and role perceived. Training is, therefore, very important. Many facilities practice with extinguishers when the extinguisher is scheduled for recharging.

Well-marked exits do not ensure life safety during a fire. Fire evacuation plans/drills are necessary so that occupants will know how to make an efficient and orderly escape. In order to be effective, exercises of the plans must be conducted as realistically as possible. Exercises should be conducted at varying times of day/night, simulate loss of exit(s), and vary fire locations.

# Activity 3.1

## Comparing Human Behavior

### Purpose

To compare human behavior responses to significant fires in places of public assembly.

### Directions

1. You will view two videos, "Beverly Hills Supper Club" (May 28, 1977) and "The Station Nightclub" (February 20, 2003).

2. Consider how human behavior and responses in both fires were similar and/or different.

3. In your table groups, list on an easel pad key factors and observations comparing and contrasting human behavior responses between the two fires.

4. Instructors will call on volunteers for their answers.

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# Activity 3.2

## Occupancy Classification Influences

### Purpose

To identify hazards and challenges likely found in different occupancies.

### Directions

1. You will work with your table group competing against the other table groups.

2. This will be a multiple-round activity, and each team will select one "artist" for each round of four. (This activity is modeled on the game "Pictionary.")

3. Without sharing the information, the instructor will give each artist an example from the following list:

    a. MultiPlex movie theatre.

    b. Basketball arena.

    c. Airport terminal.

    d. Animal hospital.

    e. Elementary school.

    f. Commercial bakery.

    g. Flammable liquid storage warehouse.

    h. Assisted-living facility.

    i. Prison.

    j. MegaMart big box retail store.

    k. College dormitory.

    l. Multifloor self-storage facility.

4. The artist will draw on an easel pad or white board the use and/or occupancy given to him/her. Words, numbers, or keyboard symbols may not be used.

5. The other class members are expected to identify the occupancy correctly as quickly as possible.

6. Once the occupancy is identified correctly, the table group that identified the picture correctly is to list on the easel pad or white board three life safety issues and three fire protection issues **likely found in that occupancy**.

7. Each drawing is worth seven points:

    a. One point for correctly identifying the use or occupancy.

    b. One point for each listed life safety and fire protection issue.

8. Additionally, other teams can accrue additional points for noting items missed on another team's drawing.

9. The team having the highest point total after four rounds is the winner.

## Activity 3.2 (cont'd)

## Occupancy Classification Influences Worksheet

| Occupancy | Life Safety Issues | Fire Protection Issues |
|---|---|---|
| Multiplex movie theatre | | |
| Basketball arena | | |
| Airport terminal | | |
| Animal hospital | | |
| Elementary school | | |
| Commercial bakery | | |
| Flammable liquid storage | | |
| Warehouse | | |
| Assisted-living facility | | |
| Prison | | |
| MegaMart big box retail store | | |
| College dormitory | | |
| Multifloor self-storage facility | | |

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## OCCUPANCY CLASSIFICATION

There are eight fundamental factors that go into the assignment of building code classifications, and they are broken into two categories: human factors and contents factors.

### Human Factors

Human factors include the physical and psychological factors that enable people to take appropriate actions to preserve their own lives or the lives of others.

- Number: the total number of occupants who might be in the building or a portion of the building.
- Density: the spatial relationships between and among occupants.
- Age: persons who are very young or very old may not have the physical or cognitive ability to escape in a timely fashion.
- Mobility: building occupants who are bedridden, incarcerated, restrained, impaired, or otherwise unable to care for themselves or self-escape.
- Awareness: the cognitive ability to respond appropriately, or the early awareness of an incident.

### Contents Factors

Contents factors include the type, amount, and environment of hazardous operations or uses.

#### Type: Categories of Materials that Create Fire or Health Hazards

- Physical hazards: items that may cause or contribute to a fire or explosion:

  - Flammable or combustible liquids,
  - Explosives and blasting agents,
  - Oxidizers, and
  - Organic peroxides.

- Health hazards: items that expose occupants to acute or chronic health effects:

  - Toxic or highly toxic materials,
  - Corrosives, and
  - Carcinogens, mutagens, and etiological agents.

- Quantity: the amount of the hazardous material in units (pounds, gallons, tons, cubic feet).

- Environment: the storage, use, handling, or transportation of the hazardous product.

These factors are weighed as one evaluates into which classification an occupancy should be placed.

- Elementary school: number, age, mobility, and awareness may be significant; hazardous materials may not.

- Woodworking factory or cabinet shop: quantity and environment of hazardous materials may be significant; occupant density may be important; age and mobility are not.

The assigned occupancy classification drives life safety fire protection requirements. Building size and height may be limited by occupants' ability to transit the means of egress systems. As buildings get taller or larger, protection for the means of egress requirements increase. In buildings four or more stories high, stairway enclosures must be at least 2 hour; they can be 1 hour or less elsewhere. This enables persons who might be at risk above the fire to get beyond it.

Construction types will correspond to increased risks. Buildings where people are incapable of self-preservation normally are limited to fire-resistive construction.

Defend-in-place strategies may be employed where people are incapable of self-preservation, since they can't get up and leave. Defend-in-place strategies include fire-resistive construction, early detection, and automatic fire suppression.

Fire protection system requirements may be tied to both life safety and hazardous conditions. Fire alarm and detection systems are installed for early occupant and fire service notification. Fire suppression detects, confines, and controls fires in their incipient stages.

Means of egress requirements are established by occupant numbers, density, and mobility. People who are in an entertainment facility where they are close together create a greater risk than less dense environments such as factories or warehouses.

## LIFE SAFETY STRATEGIES

There are four fundamental life safety strategies when dealing with fire and other threats in the built environment.

1. Full evacuation: all building occupants are educated or directed to exit simultaneously to a place of safety.

2. Partial evacuation: some building occupants are educated or directed to exit simultaneously to a place of safety.

   Phased or staged evacuation: depending on the conditions and circumstances of the event, occupants are advised to exit according to some plan that queues or stages them so all are not entering the means of egress system simultaneously.

3. Defend in place: occupants are incapable of egress or are advised to stay in place and allow building fire protection features to protect them while awaiting fire control or rescue.

4. Relocate: move to alternate location (horizontal exit or area of refuge) to await fire control or rescue.

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# Activity 3.3

## Life Safety Strategies

### Purpose

To compare four strategies for preserving life in structures during fires or other environmental emergencies.

### Directions

1. You will work in your table groups.

2. You will review the 10 emergency scenarios and evaluate life safety strategies for each event.

3. After selecting one or more strategies for each scenario, list on an easel pad your reasons for selecting them.

4. Instructors will call on volunteers for their answers.

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## Activity 3.3 (cont'd)

## Emergency Scenarios

| | Occupancy | Incident Description | Time of Day | Weather Conditions | Mitigating or Compromising Influences | Recommended Life Safety Strategy(ies) |
|---|---|---|---|---|---|---|
| 1. | Subway | Hot brake fire spreads to passenger compartment | 1723 | Clear and warm | • Subway train is more than 500 yards from nearest exit. | |
| 2. | Elementary school | Custodial closet fire in Class A combustibles | 0930 | Subfreezing and windy | • Closet opens onto central exit corridor. | |
| 3. | Convent | Unattended cooking fire | 0145 | Raining and cold | • Building is sprinklered with life safety system. | |
| 4. | Nightclub | Intentially set fire with flammable liquids | 0130 | Clear and warm | • Two of the four means of egress have been splashed with flammable liquid and ignited. | |
| 5. | Highrise office | Overheated photocopier in mail room | 1130 | Clear, cold, and windy | • Fire alarm system is inoperative.<br>• Automatic sprinklers functioning correctly.<br>• Staff had practice evacuation drill within last 72 hours. | |

| | Occupancy | Incident Description | Time of Day | Weather Conditions | Mitigation or Compromising Influences | Recommended Life Safety Strategy(ies) |
|---|---|---|---|---|---|---|
| 6. | Big box retail | Aerosol lubricant pallet burning in rack | 1450 | Cool and foggy | • Automatic sprinklers functioning correctly.<br>• Fire alarm system operating properly.<br>• Aerosol cans "rocketing" into flammable liquids racks. | |
| 7. | Manufacturing facility | Acetylene cylinder fails, discharging flammable gas | 1538 | Windy and warm | • None | |
| 8. | Mental hospital | Hurricane | 0300 | Windy, rainy, and warm | • Storm surge expected within next 2 to 3 hours. | |
| 9. | Covered shopping mall | Fire in storage area behind tenant store | 2030 | Ice storm | • Armed security guard on rampage and has barricaded himself in storage area. | |
| 10. | Multiscreen theater | Simultaneous pepper spray dispersal | 1945 | Hot, humid, and hazy | • Fire alarm system operating properly. | |

## SUMMARY

As discussed, many factors can and do influence fire-related human behavior. As the overall fire and life safety of a structure is evaluated, one should keep in mind all of these factors. It also is important for the code official to remember to evaluate the conditions on how a member of the general public would react, not how a trained firefighter or code enforcement official would react under similar circumstances.

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# *UNIT 4:*
# *EGRESS CONCEPTS*

***OBJECTIVES***

*The students will:*

1. *Compare the publicly perceived definition of "panic" with findings from empirical research.*
2. *Identify the basic components of an exit system.*
3. *Given a series of photographs, identify how individual egress components have been compromised.*

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## INTRODUCTION

Adequate egress is more than just doors and exit signs. It is a system that starts by considering the number and characteristics of the occupants, the time necessary to reach an exit, and then establishes the minimum number, size, capacity, location, and arrangement. The means of egress design must be considered as part of the total system that provides a reasonable level of life safety.

In order to determine if proper and adequate egress is provided for a specific structure, all of the following must be addressed

- occupancy classification;
- occupant load;
- minimum number of exits;
- clear opening of egress components;
- capacity of egress components;
- arrangement of egress components;
- door swing;
- travel distance; and
- special considerations.

The total means of egress system in a building or structure can consist of any or all of the following components:

- doors;
- corridors;
- stairs;
- ramps;
- exit passageways;
- horizontal exits; and
- courts and yards.

## SOME RELATED HUMAN FACTORS

The design and capacity of any means of egress system must take into consideration the physical characteristics of the human body. The tendency of individuals to avoid contact with others is a major factor in determining the number of persons who will occupy a space at any given time. If given a choice, individuals will generally establish "territories" to avoid bodily contact with others.

Studies over the years have shown that most adult males measure approximately 21 inches across at the shoulder. Additionally, the movement of individuals results in a swaying action side to side of approximately 1.5 inches. Where movement is reduced to shuffling in dense crowds or on stairways a total sway of almost 4 inches has been observed.

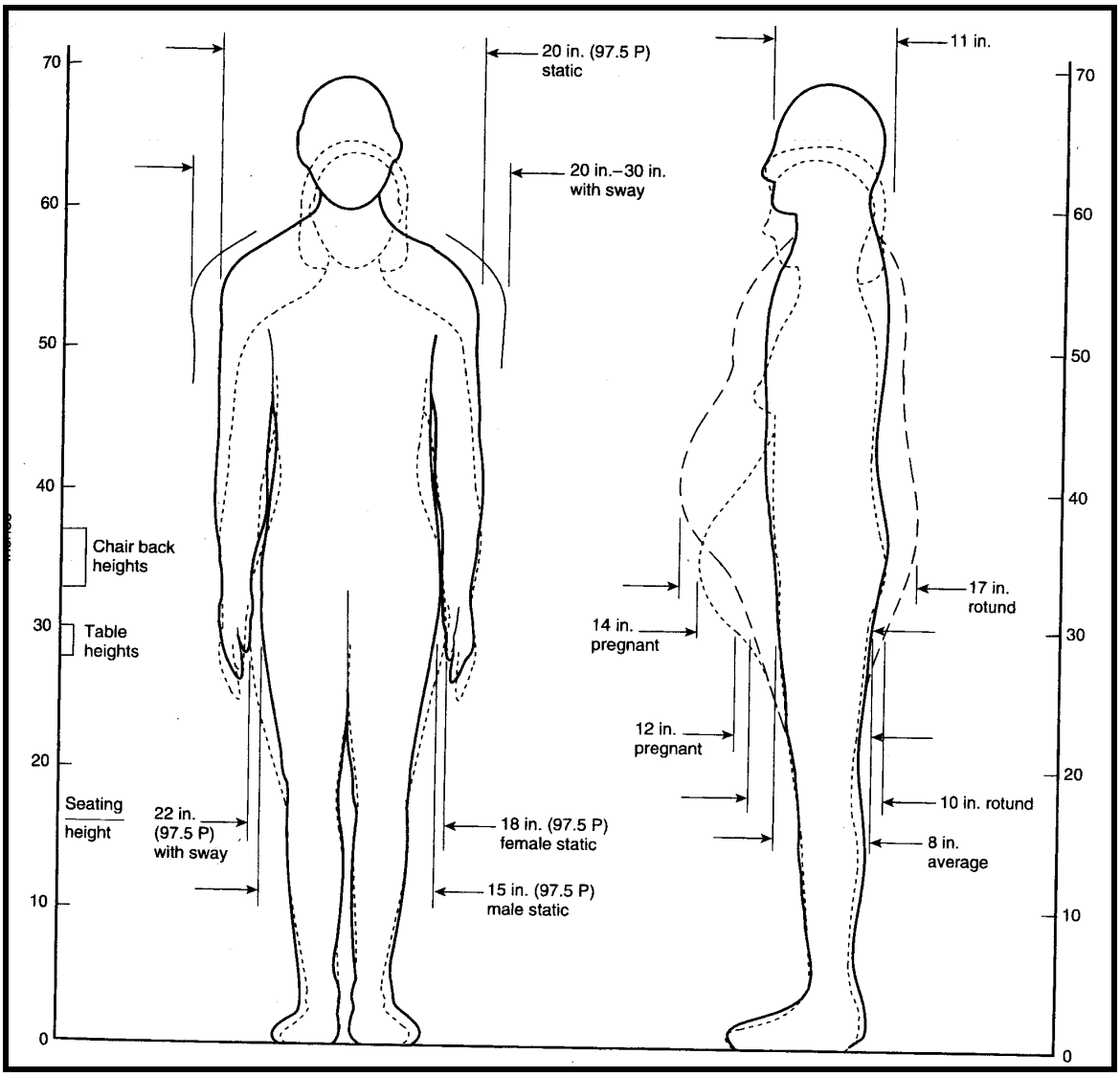


**Figure 4-1**
**Human Factors**

## Travel Speed

For the general population, the walking speed averages between 250 and 275 feet per minute for level travel and 187 feet per minute for stairs have been document from surveys. For individuals with disabilities surveys have shown the mean travel speed on level surfaces is 196 feet per minute and for stairs 75 feet per minute.

## Research into the Movement of People

At the International Life Safety and Egress Seminar in 1981, J.L. Pauls presented some interesting information regarding some of the assumptions made about the movement of people and its effect on the effectiveness of a building's means of egress. The following is abstracted from his remarks.

> Some egress rules were developed in their present form twenty years before research was done.
>
> Research on people's movement falls into two schools: the carrying capacity school which examines exit flow capacity, and the human response school which says that exit capacity may be a necessary condition for safe egress, but it is not a sufficient condition. In the former, the "safe end" of the egress route is emphasized as the key point where egress is evaluated. The human response school looks at what happens at the other end of the route--the threatened end of the egress route.
>
> The former assumes that people will, upon hearing an alarm, drop what they are doing and immediately evacuate in an orderly fashion, without interacting with each other. Actually, people tend to ignore or downplay the initial fire cues, eventually they investigate conditions, compare with their experience, and then decide on actions that may have little to do with what is assumed in code rules for egress.
>
> Such activities take time. Another finding is that familiar entry routes are more likely to be used for evacuation than egress routes that have never been experienced before. Consequently, routes that are being counted on to "drain" the building of its occupants may be disregarded in an actual evacuation.
>
> Traditional exit technology also relies on what is called the "hydraulic model." There are three assumptions in the hydraulic model: occupants are alert, able bodied, and ambulatory; fire safety depends on the safe end of the evacuation system; and there is a high-density building population that will tax the capacity of the exit system.
>
> There are two phases to evacuation: the time to start and the movement phase. The hydraulic model deals only with the latter. Liquid flow or ball-bearing models do not account for the fact that people take time to investigate the situation, help one another or that they have different degrees of familiarity with particular routes.

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## Activity 4.1

## Is it Panic?

### Purpose

To compare the publicly perceived definition of "panic" with findings from empirical research.

### Directions

1. Reflect on your observations from the two videos from Unit 3: Fire-Related Human Behavior: "The Beverly Hills Supper Club" and "The Station Nightclub."

2. Describe how you would characterize the public's perception of:

   a. The components of "panic."

   _____

   _____

   b. The conditions that might create "panic."

   _____

   _____

   c. The potential outcomes of "panic behavior."

   _____

   _____

3. Your instructor will list on an easel pad or a whiteboard the key factors and observations describing public perception about "panic."

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## Activity 4.1 (cont'd)

**Source: The SFPE Handbook of Fire Protection Engineering, 2nd Edition**
**Society of Fire Protection Engineers**
**Bethesda, Maryland**
**© 1995**

### Panic Behavior

The concept of panic behavior is the nonadaptive behavioral response that is always discussed following fire incidents such as the Beverly Hills Supper Club fire where multiple fatalities occurred.

According to most definitions, panic is a flight or fleeing type of behavioral response that also involves extravagant and injudicious effort. Panic is not likely to be limited to a single individual but may be mimicked and adopted by a body of persons. Schultz has defined a panic type of behavior reaction from his simulation experiments in the following manner:

> *A fear-induced flight behavior which is nonrational, nonadaptive, and nonsocial, which serves to reduce the escape possibilities of the group as a whole.*

The concept of panic is often used to explain the occurrence of multiple fatalities in fires even when there is no physical, social, or psychological evidence indicating that competitive, injudicious flight behavior actually occurred. Representatives of the media and public officials often label various types of fire-incident behavioral responses as panic. The evidence accumulated from interviews with participants and the questionnaires completed by occupants provided no evidence of the classical group type of panic behavior with competitive flight for the exits in the Beverly Hills Supper Club fire.

Sime has indicated that panic as a concept is primarily a description of the behavior, not an explanation of the behavior. He pointed out that the concept is used to support the introduction of requirements in building laws or ordinances to provide for the fire safety of the building occupants. Sime has also very aptly shown the difference between the use of the concept to describe other persons' behavior in a fire incident, and the use of the concept to describe an individual's behavior which is accompanied by a high state of concern and anxiety. As Sime has indicated, simply because an individual identifies behavior as being associated with a panic reaction, this does not necessarily identify the behavior as being the classic panic type behavioral response. Sime also indicates the outcome of the behavior, as previously discussed, affects its labeling and that the actual behavior of people in a fire is most likely to be misinterpreted when the outcome of the fire incident has been unfortunate.

As Sime indicated, the use of the concept of panic must be separated from the use of the terms "anxiety" or "fear." The concept of self-destructive or animalistic panic type behavioral responses to fire incident stimuli such as the presence of flames or smoke has not been supported by the research on human behavior in fire incidents. As indicated by Sime, Quarantelli, and others, panic behavior in which the flight response is characterized by actual physical competition between the participants and personal injuries is rare.

In his interview study of 100 participants of single-dwelling residential fires, Keating reported no instances of panic behavior and instead found primarily altruistic, helpful behavioral responses.

Ramachandran, in his review of studies on human behavior in fire in the United Kingdom, has developed the following conclusion relative to nonadaptive behavior:

> In the stress of a fire, people often act inappropriately but rarely panic or behave irrationally. Such behavior, to a large extent, is due to the fact that information initially available to people regarding the possible existence of a fire and its size and location is often ambiguous or inadequate.

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## SOME RELATED HUMAN FACTORS (cont'd)

### General Assumptions on the Movement of People in Fire

In Section 3, Chapter 13 of the SFPE *Handbook on Fire Prevention*, Guylene Proulx provides the following summary of the general conclusions that can be drawn regarding the movement of people in fire.

> Panic is very rare even in fires. Normal patterns of behavior, movement of route choices, and relationships with others tend to persist during emergency situations.
>
> Individual's behavior tends to be altruistic and reasonable, especially in light of the limited and ambiguous information available at the time of the event.
>
> After perceiving a fire cue, such as the fire alarm signal or smelling smoke, people often ignore these initial cues or spend time investigating, seeking information about the nature and seriousness of the situation, which creates a delay before starting the evacuation movement.
>
> Faced with ambiguous information and short time for decision making, people are likely to apply a well-run decision plan when choosing an evacuation route, consequently moving toward their most familiar way out the building.
>
> Evacuation, and response to fire generally, is often a social response; people tend to act as a group and to attempt to evacuate with people with whom they have emotional ties.
>
> Problems that are encountered during normal building use will tend to persist and exacerbate situations in emergencies. Included are faulty communication, circulation hazards, wayfinding problems.

### Delay Time to Start Evacuation

The following information is taken from *Fire Safety Engineering in Buildings, Part 1, Guide to the Application of Fire Safety Engineering Principles*, Table 21, British Standard Institute, DD240, London, 1997.

## Table 4-1
## Delay Time to Start Evacuation

| Occupancy Type | W1 (min) | W2 (min) | W3 (min) |
|---|---|---|---|
| Offices, commercial and industrial buildings, schools, colleges, and universities (Occupants awake and familiar with the building, the alarm system, and evacuation procedure) | <1 | 3 | >4 |
| Shops, museums, leisure sport centers, and other assembly buildings (Occupants awake but may be unfamiliar with building, alarm system, and evacuation) | <2 | 3 | >6 |
| Dormitories, residential midrise, and highrise (Occupants may be asleep but are predominately familiar with the building, alarm system, and evacuation procedure) | <2 | 4 | >5 |
| Hotels and boarding houses (Occupants may be asleep and unfamiliar with building, alarm system, and evacuation procedure) | <2 | 4 | >6 |
| Hospitals, nursing homes, and other institutional establishment (A significant number of occupants may require assistance) | <3 | 5 | >8 |

W1: Live directives using a voice communication system from a control room with closed-circuit television facility, or live directives in conjunction with well-trained, uniformed staff who can be seen and heard by all occupants in the space.
W2: Nondirective voice messages (prerecorded) and/or informative warning visual display with trained staff.
W3: Warning system using fire alarm signal and staff with no relevant training.

# Activity 4.2

## Identifying Means of Egress Components

### Purpose

To identify the basic components of an exit system.

### Directions

1. Refer to the sketch on the next page.
2. Using the four choices below, label each component of the means of egress.
    a. Exit access.
    b. Exit.
    c. Exit discharge.
    d. Public way.
3. The class will review answers at the end of the activity.

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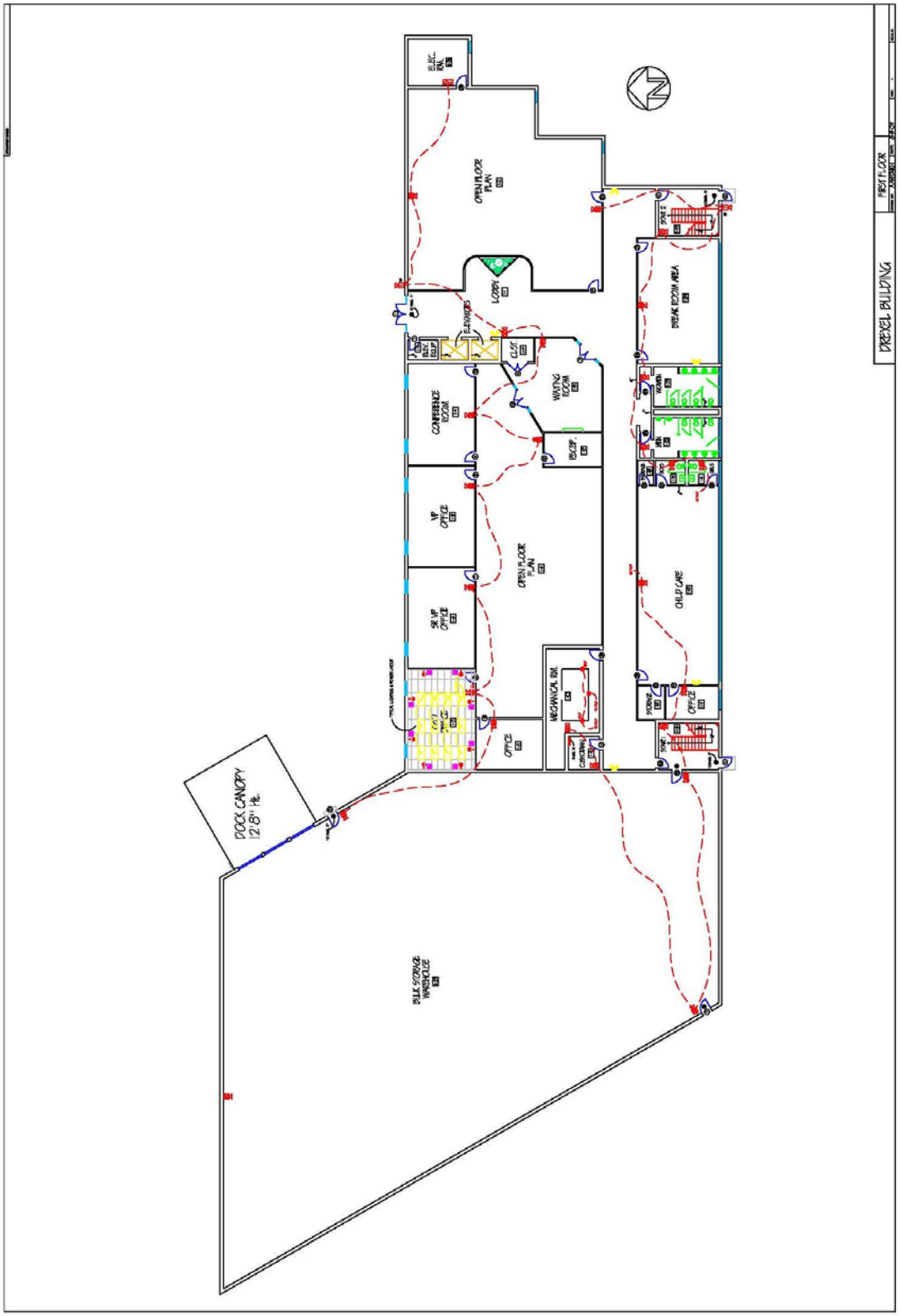
## Activity 4.2 (cont'd)



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## MEANS OF EGRESS ELEMENTS

### Calculation of Egress Time

The prediction of the movement of individuals during emergency egress is an essential aspect of a performance based design approach. In general, life safety can be achieved if the required safe egress time (RSET) is shorter than the available safe egress time (ASET). ASET is defined as the time when fire conditions within the space become untenable.

RSET can be calculated as follows:

$$RSET = t_d + t_a + t_o + t_i + t_e$$

Where

$t_d$ = time from ignition to detection

$t_a$ = time from detection to notification of occupants of a fire emergency

$t_o$ = time from notification until occupants decide to take action

$t_i$ = time from decision to take action until evacuation commences

$t_e$ = time from the start of evacuation until it is completed

## FUNDAMENTALS

There are three major factors to consider when evaluating both the life safety risk and the adequacy of the egress system: time, characteristics of the occupants, and nature of the fire.

### Time

Providing life safety to occupants who are capable of exiting a building can be defined in terms of a safe egress time--the time interval from detection (or notification) to the hazard threshold (time to reach lethal conditions). However, the time interval between detection and ignition also must be considered. Therefore, three times must be considered, time to ignition, time to detection, and time to hazard threshold. (See Figure 4-2.)

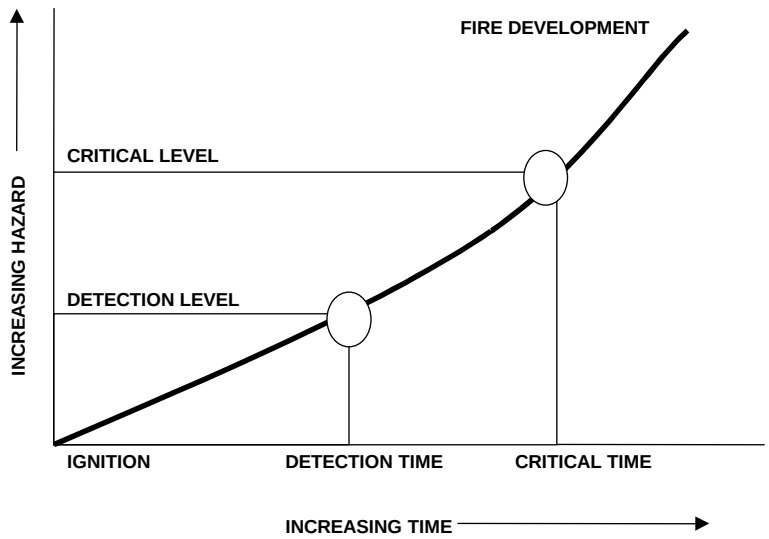


**Figure 4-2**
**Rate of Deterioration of the Environment as a Fire Progresses**

## Characteristics of the Occupants

The ability and likelihood of occupants to respond to a fire emergency are affected by six factors: age, mobility, awareness, knowledge, density, and discipline. The various occupancy classifications previously discussed attempt to generalize the occupants' characteristics within each occupancy classification.

**Age**. The age of the occupant affects his/her ability to negotiate portions of the means of egress. For example, young children will have more difficulty in traversing a stair than will young adults. Therefore, it is common to find code requirements addressing the location of preschool, kindergarten, and first grade classrooms in an elementary school. Statistically, the very young and the very old are at the greatest risk from fire. Age usually has an effect on the other five occupant characteristics.

**Mobility**. Some occupants are not capable of responding to a fire emergency, or they respond with some degree of difficulty. For example, the codes generally assume that the occupants of a health care facility will not be capable of self-preservation. Thus, the codes will address requirements for staff training to assist the occupants, and for building compartmentation (smoke barriers and horizontal exits) to facilitate evacuation to an area of refuge. Likewise, the occupants of a correctional facility are generally not as mobile as the general population. The mobility of the occupants also affects the components permitted within the means of egress. For example, fire escape ladders and alternating tread devices usually are permitted only when the area is to be occupied by able-bodied individuals.

The increasing awareness of the need to provide egress for the physically disabled will have a significant effect on the egress provisions of the various codes. Some code requirements, such as minimum clear-width dimensions of doors, are related to the need for a person in a wheelchair to

use the door. It is expected that additional code requirements for accessible egress routes and areas of refuge for the physically disabled will be incorporated into the codes soon.

**Awareness**. The awareness factor involves occupants' ability to notice a fire emergency. For example, in residential occupancies it is assumed that the occupants will be asleep at some time. Therefore, the package of protection features must consider that a fire could develop without the occupant being aware of the changes to the environment caused by the fire. The codes contain other provisions related to awareness, including the height of movable partitions in open offices and the need to have mezzanine areas open to the space below so that the occupants can detect a fire.

**Knowledge**. Through increasing public fire safety education, it is anticipated that the general population will have an increasing knowledge of fire and life safety. This increasing knowledge should result in proper responses to fire emergencies. However, knowledge also involves occupants' familiarity with the environment and egress routes. Code provisions for single-family dwellings differ from those for hotels because occupants of single-family dwellings are more familiar with the layout of the unit and available egress or escape routes.

**Density**. Occupant density will have a dramatic impact on the time necessary to evacuate a given space. High densities can increase the time necessary to reach an exit both in speed of travel and in queuing at the entrance to the exit. Codes may vary with respect to maximum densities permitted to provide some controls on this factor.

**Discipline**. Some occupancies, by the nature of the use, will provide a higher degree of discipline which will affect how the occupants respond. For example, the occupants of an elementary school are usually in a more disciplined environment than the occupants of mercantile or retail establishments. It is assumed that the occupants in the elementary school will respond to the direction of their teachers more than the occupants of a store may respond a salesclerk's directions.

## Nature of the Fire

The likelihood of a fire (ignition potential), the fire growth rate, and the spread of smoke and fire are also major factors in evaluating occupants' life safety. The package of code requirements related to life safety from fire address all three factors in attempting to provide an acceptable level of life safety.

The potential for ignition relates to available ignition sources and the proximity and configuration of available fuel sources. Obviously, normal functions within a building, e.g., lighting, heating, and cooking, introduce potential ignition sources. Other activities associated with the occupants, such as smoking, introduce additional ignition sources. Furnishings, decorations, clothing, and other building contents provide fuel sources with varying degrees of ignitability. Frequently, codes will address these issues by requiring smoking restrictions, clearances from combustibles, treated fabrics, and separation of certain hazardous areas.

Once ignition occurs, the fire growth rate becomes the most important factor. As previously discussed, life safety involves avoiding exposure to the harmful effects of the products of combustion. Therefore, the hazard increases as a function of time based on the growth of the fire, usually measured in terms of heat release rate. Early in the fire, the fuel is the most important factor in determining the fire growth rate. However, the surrounding environment also becomes critical in later fire development. For example, a fire in the corner of a room will be more severe than the same fire located in the center of the same room. The location of the fire in the room, the ceiling height of the room, and the interior finishes on the walls and ceiling will be critical in assessing life safety.

Depending on the fire growth rate and smoke spread from the room, a room fire poses a life safety hazard to other building occupants. The codes generally attempt to contain the fire to the room of origin with either passive (compartmentation), active (automatic sprinklers), or a combination of both fire protection features. Vertical fire spread also is critical to the life safety of the occupants. Therefore the construction of the floor and the protection of vertical openings are critical. At times, the codes also will attempt to limit, by fire or smoke compartmentation, the number of people that might be exposed to a given fire. Finally, smoke control systems may be required to control or restrict the spread of smoke to adjacent areas or floors.

## Fundamental Principles of Life Safety

These fundamental requirements provide some basic life safety principles, which are the basis of many life safety code requirements:

1. **To provide for adequate exits without dependence on any single safeguard**. The exits must be sufficient in capacity for the number of occupants, and a single failure shall not result in an unacceptable level of life safety.

2. **To ensure that construction is sufficient to provide structural integrity during a fire while the occupants are exiting or in an area of refuge**. Note that from an occupant life safety perspective, the structural integrity need only be sufficient for safe egress time. Additional protection would be necessary for the safety of firefighters during interior fire suppression activities.

3. **To provide exits that have been designed to the size, shape, and nature of the occupancy**. The use of the space or building determines the design requirements for the exits. A 10,000-square-foot storage building requires neither the same number or capacity of exits as a 10,000-square-foot place of assembly due to the number and characteristics of the occupants. Because of the nature of the fire, a building in which bricks are stored does not have the same exit requirements as a building in which flammable liquids are stored.

4. **To ensure that the exits are clear, unobstructed, and unlocked**. The occupants of the building should have a clear path of travel to the exits and control over any component of the egress system. The occupants should be able to exit a building easily without the use of any special knowledge, effort, keys, or tools. It should be noted that, in certain instances, codes will allow some deviation from this fundamental principle, provided the occupants have the necessary knowledge to effect safe egress.

5. **To ensure that the exits and routes of escape are clearly marked so that there is no confusion in reaching an exit**. While the need for exit marking does vary from occupancy to occupancy, depending on the occupants' familiarity with the building, the codes generally require some degree of exit marking in case occupants become confused or disoriented.

6. **To provide adequate lighting**. Adequate lighting is essential to the safe use of the egress system, especially components such as stairs.

7. **To ensure early warning of fire**. This does not necessarily mean that automatic detection is required in all buildings. Depending upon the awareness of the occupants and their ability to detect changes in their environment, automatic detection may not be necessary. It also should be noted that, from a life safety standpoint, when automatic detection is required it usually involves smoke detection and not heat detection, unless the space is not occupied and is separated from occupied areas.

8. **To provide for backup or redundant exit arrangements**. With a few limited exceptions, the codes require at least two exits to be accessible from every area.

9. **To ensure the suitable enclosure of vertical openings**. Many large-life-loss fires have occurred in buildings with unprotected vertical openings. The vertical openings allow smoke and fire to spread easily to adjacent floors with little advance warning for the occupants on the adjacent floors.

10. **To make allowances for those design criteria that are tailored to the normal use and needs of the occupancy**. While adequate fire protection and life safety are critical, they are not the primary purpose for constructing a building. Therefore, it is critical that codes provide an acceptable level of safety without creating an undue hardship or inconvenience. This is not to say that the needs of the operation or use should compromise life safety, but rather, that attempts should be made to provide life safety without interfering with the operation or use of the building. For example, it is obvious that locks must be permitted in correctional facilities. The codes recognize this and provide acceptable life safety by addressing the operation and reliability of the locking system without compromising security.

## Total Concept of Life Safety

Using the fundamental principles and the life safety factors, a systematic approach to life safety can be developed. In theory, if one component of the following list can be accomplished with total certainty (100-percent assurance), the remaining components are not necessary. However, since total certainty typically is not achievable, codes tend to incorporate all of the following components of life safety.

The Total Concept of Life Safety involves the following:

- **Prevent Ignition**. Code requirements that address potential fuel sources, the ignitability of materials, and clearances to combustibles are examples of provisions that prevent ignition.

- **Detection of Fire**. The detection of fire may be by the occupants or by automatic detection.

- **Control of Fire Development**. Codes address controls on fire development primarily by restrictions on interior finishes. However, more recently codes also have addressed the heat release rates of upholstered furniture and mattresses in certain occupancies.

- **Confinement of the Effects of Fire**. Confinement typically is accomplished through passive fire protection features such as fire barriers, occupancy separation walls, fire separation walls, tenant separations, firewalls, area separation walls, corridor walls, and smoke barriers.

- **Extinguishment of Fire**. As with the detection of the fire, the extinguishment may be by manual or automatic means.

- **Provision of Refuge and/or Evacuation Facilities**. The occupants must be capable of exiting the building, or have a safe area of refuge within the building.

- **Occupant/Staff**. While the human behavior aspect of life safety is the most difficult to control, fire experience and research have indicated that many people will respond appropriately if they have received proper training.

## PEOPLE MOVEMENT

With respect to life safety, the primary concern is the safety of the occupants during the fire. As such, there are two options available: evacuation to a place of safety, or defend in place. Each of the strategies requires specific actions and protection features to be successful. While some are quick to point out that most people die in the process of evacuation and, therefore, we should direct our efforts to defending in place, there is no one single approach which is applicable to all occupancies or to all fire scenarios.

## Evacuation

The protection features required for safe evacuation can be divided into two main categories: actions necessary to cause occupant movement, and protection features required to provide an evacuation route (means of movement).

With respect to occupant movement, the first action required is to detect the fire. Depending on the occupancy and, in particular, the awareness of the occupants, the detection may be by manual or automatic means. Fire growth rate is another factor to consider in determining whether the detection should be manual or automatic. A contributing factor identified in many fatal fires is the delay in discovery of the fire. This results in an inadequate amount of time to accomplish egress.

Once the fire is discovered, a means must be available to notify the other occupants in the building. Depending on the size, configuration, and use of the building, such notification may require a fire protective signaling system. The fire protective signaling system may be initiated by automatic or manual means. While the automatic initiation of the fire protective signaling system decreases the time between detection and notification, such systems also are prone to a high number of unwanted alarms. Unwanted alarms have the potential for creating a "cry-wolf" syndrome with the building's occupants.

Detection and notification are effective only if the occupants have been taught how to respond to a fire emergency. In many cases, normal public education efforts are sufficient to provide adequate instructions to the occupants. It should be noted, however, that there is no one standard audible fire alarm signal in the United States; therefore, the occupants must first identify the alarm signal as a fire alarm. In larger and more complex buildings, specific instructions must be provided to the building's occupants. In highrise buildings, the concept of partial or zoned evacuation often is used. The occupants in the vicinity of the fire are evacuated to an area of refuge; further evacuation occurs as required. Such an evacuation strategy often requires the use of a voice communication system to provide the instructions appropriate to the specific fire.

## Provide Movement Means

If the occupants are to be evacuated, the egress system clearly must have adequate capacity for the number of occupants within the building or area being evacuated. The capacity of exits usually is determined by calculating the occupant load (to be discussed in the next section) and multiplying by a factor identified in the codes for a specific egress component (i.e., door, stair, ramp, etc.). The capacity of the exits includes access to the exit as well as the exit itself, and should be based on the highest anticipated (calculated) occupant load.

It is not sufficient merely to provide doors and stairs of adequate capacity. The egress system must allow for the safe movement of the occupants to a safe area. A safe area may be a public way (as defined in the codes) or an area of refuge within the building. For example, travel through a horizontal exit is considered as egress to a safe area even though the occupants are still within the building.

The exits must be accessible to the occupants. Access to exits involves the path of travel to the exit. The occupant should have control over anything within the egress path without the use of any special knowledge, effort, tools, or keys. Aisles, corridors, and other egress routes shall be clear and unobstructed.

Finally, the egress path shall be protected against the products of combustion and provided with structural integrity. The codes also usually require that once an occupant enters an area with a certain level of protection, the level of protection shall be maintained or increased throughout the remainder of the egress route. For example, once an occupant enters a corridor which is separated from other areas by construction having a fire-resistance rating of at least 1 hour, the corridor should lead to an outside door, horizontal exit, stair, or other egress component with a similar or higher level of protection. The occupant should not be required to leave the protected corridor and travel through a room to access a stair. It should be noted that many codes do not require the floors, beams, columns, or other structural elements supporting corridor walls to have the same fire-resistance rating as may be required for the corridor walls.

In addition to some degree of fire resistance, which varies depending on the occupancy, size, and construction of the building, the egress paths also must be protected against the products of combustion. For this reason, automatic closing corridor and stairway doors must close upon the detection of smoke and not by fusible link or other heat-actuated device. There is substantial variation among the codes on the degree to which egress routes must restrict smoke spread. However, the requirements typically vary by occupancy classification and the presence of automatic sprinkler protection.

While it was stated earlier that life safety is a function of time, the codes do not identify a required evacuation time for buildings. The required egress widths are based on a flow time concept, which is the amount of time required for a given number of people to flow through a point (e.g., door opening). However, total evacuation time would require travel to the door, travel through the door, and then travel to the designated safe area. There are, however, some time expectations upon which some of the code requirements have been developed.

## Defend in Place

One of the difficulties in implementing a defend-in-place concept is the need to restrict the movement of the occupants. People in fire emergencies typically locate an exit and get out of the building. In fact, this is what our public fire safety education emphasizes. Therefore, in order for the defend-in-place concept to be effective, a means must be provided to restrict the movement of the occupants. This is why the defend-in-place concept often is limited to health care and detention and correctional occupancies. The very nature of the use of such facilities involves occupants who are not capable of self-preservation, and therefore are not capable of self-assistance. In such occupancies, arrangements can be made so that the fire protective signaling system is intended primarily to notify the staff, and not necessarily all the occupants within the building, of the fire emergency.

If the occupants' movement can be restricted, the only other protection feature required is to protect the area against the products of combustion and to provide structural integrity. Such protection is often more severe than the protection required for evacuation since the duration of exposure typically will be longer. Whereas it may take 90 seconds to evacuate a fire floor, the defend-in-place concept requires occupants to remain in the protected area for the duration of the fire.

One means of providing the necessary protection is prompt extinguishment of the fire. For this reason, many codes require the installation of automatic sprinkler protection in health care and detention and correctional facilities. Other protection features may include the proper equipment and training to suppress fires manually in their incipient stage, prior to sprinkler actuation. The advent of quick response and residential sprinklers has helped in the implementation of the defend-in-place concept. In fact, tests have demonstrated the ability of such sprinklers to maintain tenability in the room of fire origin during certain fire exposures.

In some instances, the desired protection strategy may provide for evacuation **and** defend in place. For example, the fire emergency plan for many highrise buildings indicates that only certain occupants need to evacuate. Occupants on other floors may remain in place unless conditions develop that require their evacuation. Total evacuation of buildings typically is only practical in small buildings with able-bodied occupants. However, as defined herein, the evacuation strategy also may include the evacuation of the occupants to an area of refuge.

## OCCUPANT LOAD

The codes use factors for determining the occupant load which relate to the anticipated density of people within the area. These factors are the lowest density that may be used in calculating an occupant load. Provisions also are made for increasing the load, as long as all other requirements for the means of egress are provided. Care should be taken in permitting increases, as occupant loads with a density of one person/5 square feet or greater will have a negative impact on the movement of persons attempting to egress.

For example, the occupant load factor for office areas typically is one person per 100 square feet, but the occupant density ratio in some government office buildings has been determined to be one person per 60 square feet. Therefore, the occupant load factors in the codes should be used as a base number which can be exceeded when appropriate.

Some occupant load factors are based on the gross floor area, and some are based on the net floor area. The gross floor area is the area within the inside perimeter of the outside walls. The net floor area is the actual occupied floor area, not including accessory unoccupied areas or the thickness of the walls. For example, a rectangular room has a measured length (wall to wall) of 100 feet and a measured width of 50 feet. Within the room is a storage closet of 8 square feet, encased columns which total 12 square feet in area, and a fixed piece of furniture, such as a bar, of 24 square feet. The gross and net floor areas would be calculated as follows:

Gross Floor Area

=100 ft.x50 ft.=5,000 sq. ft.

Net Floor Area

=5,000 sq. ft.-(8+12+24) sq. ft.

=5,000 sq. ft.-44 sq. ft.

=4,956 sq. ft.

## Occupant Load Calculation Examples

1. If the above room were used as an office area with an occupant load of one person per 100 square feet (gross), the calculated occupant load would be

   Occupant Load=(5,000 sq. ft.)/(100 sq. ft./person)

   =50 people

2. If the above room were used for concentrated assembly, and the occupant load factor of one person per 7 square feet (net) were used, the calculated occupant load would be

   Occupant Load=(4,956 sq. ft.)/(7 sq. ft./person)

   =708 people

3. The above room is to be used as an office area for a department that is expanding. Presently, the department has 60 people working in a 4,800 square-foot space. The department head advises you that the additional area is so that the staff can expand, and that the density of employees will be about the same as the existing space. The occupant load of this area would be determined as follows:

   Occupant Load Factor=(4,800 sq. ft.)/(60 people)

   =80 sq. ft./person

   Occupant Load=(5,000 sq. ft.)/(80 sq. ft./person)

   =62.5 persons

The third example illustrates two points. First, the density of the occupants is greater than one person per 100 square feet as was used in the first example. Therefore, an occupant load factor representing the actual intended use must be determined. An alternative would be to use the

actual number of people anticipated to occupy the area, if the number is known. The second point is that the calculation will not always result in a whole number. The codes generally do not specify what to do with respect to rounding off. General mathematical procedures of rounding off to the nearest whole number should be sufficiently accurate. Therefore, in this example, the calculated occupant load would be 63. Some code officials prefer always to round up to the next highest whole number. Such a procedure is acceptable and will be more conservative.

## EXIT SYSTEMS

Means of egress systems are quite simple in theory. They are ways of safely getting occupants from any part of the building to the outside. The means of egress system is composed of three distinct parts: exit access, exit, and exit discharge. It is important to realize that both exit access and exits will, at times, consist of doorways, corridors, exterior exit balconies, smokeproof enclosures, stairways, ramps, exit passageways, horizontal exits, exit courts, or yards, depending on whether or not they are protected or rated.

**Exit access** is that part of the system that leads from any point in the building to a protected (rated) way. This part is essentially unprotected. This is the portion of the means of egress that is considered in determining the travel distance.

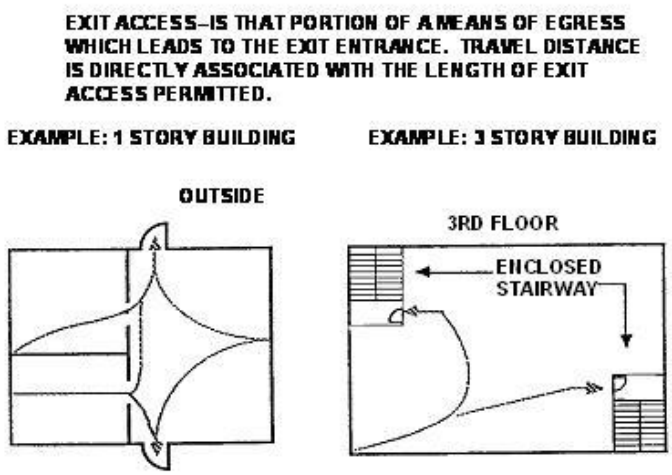


**Figure 4-3**
**Means of Egress--Exit Access**

**Exit** is that part which is essentially protected, such as a rated corridor or an exit passageway; it may be as simple as a doorway.

**EXIT–THAT PORTION OF A MEANS OF EGRESS WHICH IS SEPARATED FROM OTHER SPACES OF A BUILDING OR STRUCTURE BY CONSTRUCTION OR EQUIPMENT TO PROVIDE A PROTECTED WAY OF TRAVEL TO THE EXIT DISCHARGE.**

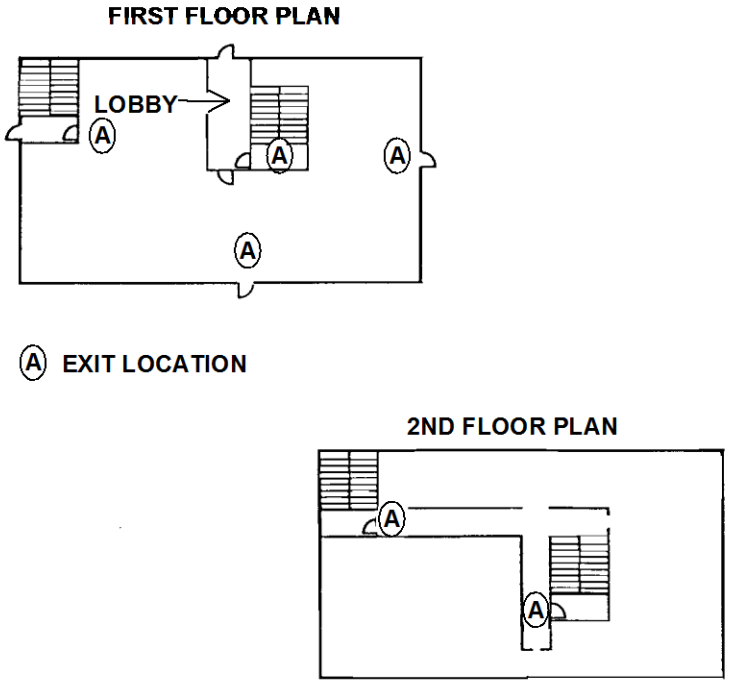


**Figure 4-4**
**Means of Egress--Exit**

**Exit discharge** is that part of the system where the person leaves the building and enters a public way.

**Public way** is a street, alley, or similar parcel of land essentially open to the outside air deeded, dedicated, or otherwise permanently appropriated to the public for public use and having a clear width and height of not less than 10 feet.

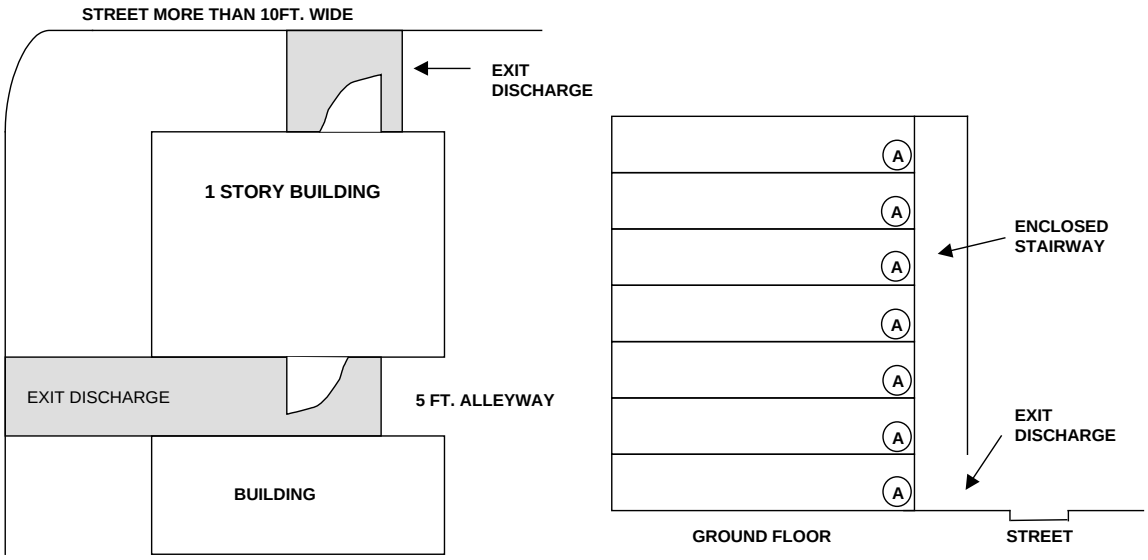


**Figure 4-5**
**Means of Egress--Exit Discharge**

The basic concept of exiting provides that all persons are entitled to be able to get out of any structure. It also insists that people within a structure have control of the elements of the exiting system. This means that all hardware on doors must be operable from the inside without the use of a key, without having any special knowledge, or without exerting any special effort.

Once the exit size, or number of exits, and/or the protection level have been established, they may not be reduced. This protection level must extend all the way to the public way.

## MINIMUM NUMBER OF EXITS

When 50 or more people are assembled in one room, two exits, remote from each other, are required. There are some exceptions to the magic number of 50, depending on the type of occupancy or hazard.

At a minimum, two exits are required from floors above the level of exit discharge. Three remote exits are required from any story or portion thereof with 501 to 1,000 occupant load. Four remote exits are required where there is an occupant load of 1,001 or more.

When the occupants of one room or floor must exit through another room or floor, both of the occupant loads must be added together to reach the number of required exits. However, if the occupant load of a second or third floor exits into an enclosure and then to the outside, it is assumed that the first floor will exit before the second gets there, and so on.

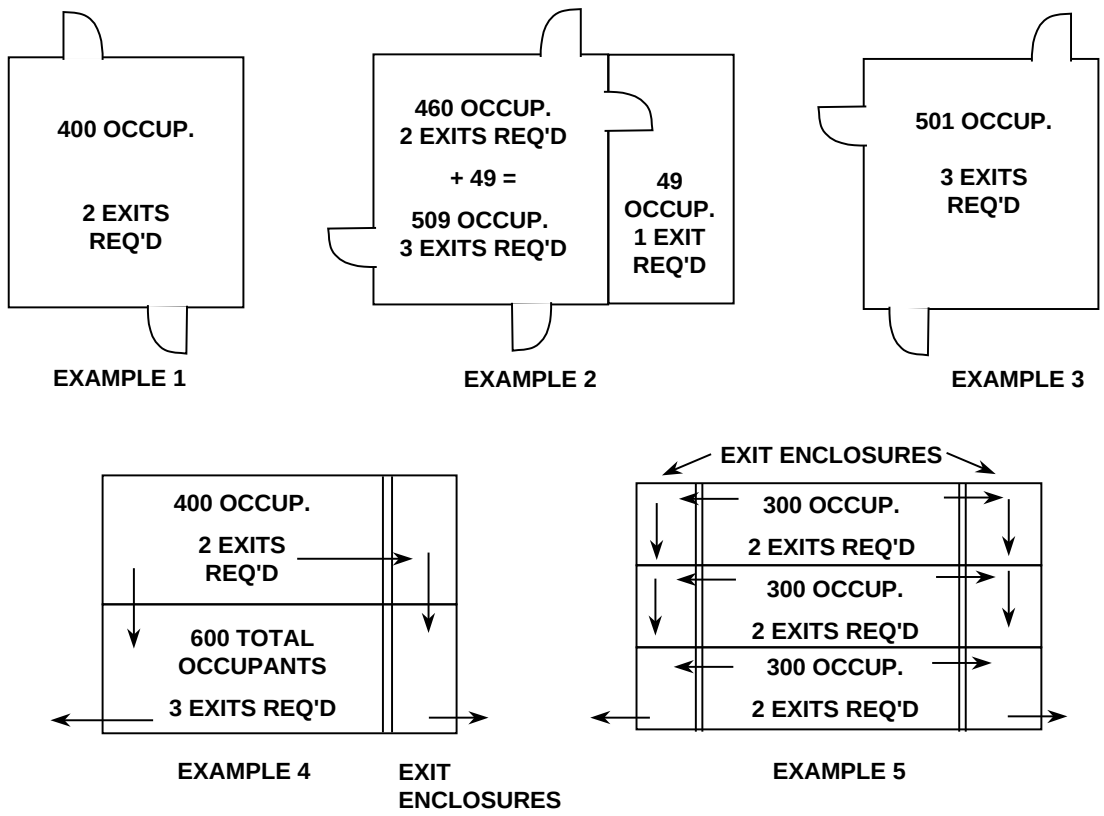


**Figure 4-6**
**Exits Required**

## Arrangement or Remoteness

The term "remote" has been defined in different ways. The intent always has been to have the exits separated so that if an incident were to render one unusable, occupants could use the others. The base criterion now used is that when two or more exit or exit access doors are required, they shall be located a distance not less than one-half the maximum overall diagonal dimension of the building or area to be served, measured in a straight line between the nearest edge of the exit doors or exit access doors.

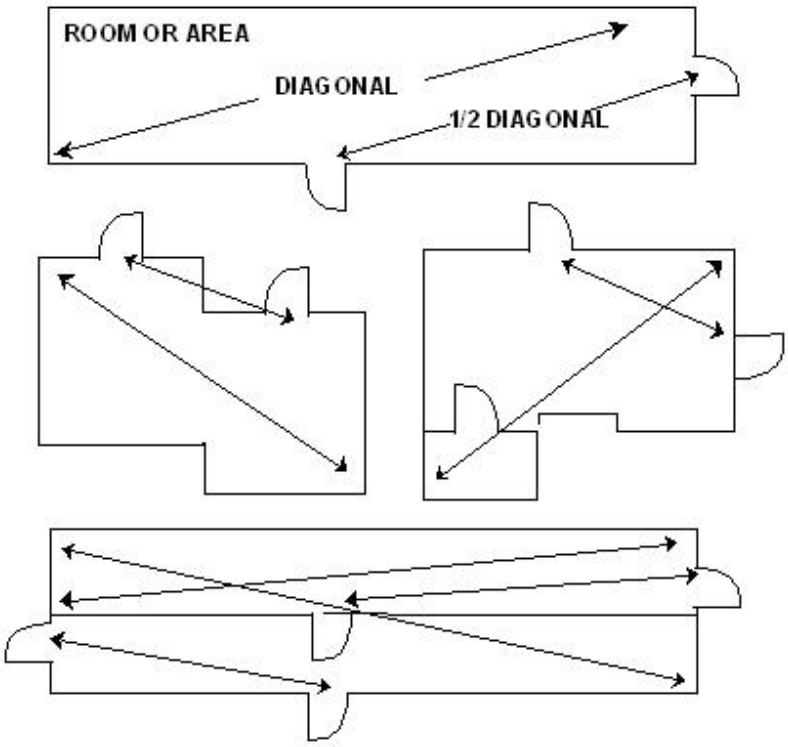


**Figure 4-7**
**Arrangement of Exits**

### Special Rules/Considerations

For places of assembly, the basic rule for years was that the main exits have sufficient capacity to handle at least 50 percent of the total occupant load and additional exits must have sufficient capacity to handled two-thirds of the total occupant load. Over the years, this requirement was modified to change the two-thirds requirement to 50 percent.

As result of the fire at The Station Nightclub in West Warwick, Rhode Island, in 2003, changes have been made in the codes to reflect documented human behavior. In new construction the main exit now must have the capacity to handle at least two-thirds of total occupant load. This applies to bars with live entertainment, dance halls, discotheques, nightclubs, and assemblies with festival seating.

## CAPACITY DETERMINATION

### Exit Capacity

For many years the basic concept used in determining the capacity of the means of egress was the "unit of exit width." A "unit of exit width" was 22 inches, and was considered the minimum necessary for the orderly, single-file movement of individuals along a passageway. This is based primarily on a study conducted in 1935 by the-then National Bureau of Standards (NBS) (now

the National Institute of Standards and Technology (NIST)) entitled "Design and Construction of Building Exits."

This study, along with one conducted by the London Transit Board in 1958, "Second Report of the Operational Research Team on the Capacity of Footways," agreed that this dimension would accommodate the shoulders of an adult male. On this basis, the NBS study found that a stairway width 44 inches and doorway opening of 36 inches were the minimum necessary for the smooth movement of occupants.

Each unit of exit width is credited with being able to accommodate a designated number of reasonably alert, healthy individuals, the number being dependent on whether they are moving along a level path of travel, a ramp, or the steps of a stairway. As would be expected, the figure is lower for stairways, which require a higher level of agility, watchfulness, and the energy to negotiate. Studies revealed that people are capable of moving up and down stairs at essentially the same speed.

For level travel, each unit of exit width had a capacity of 100 persons. For stair travel, the capacity was set at 60 persons for each unit of exit width. For calculation purposes, factions of a unit comprising 12 or more inches, added to one or more full units, were counted as one-half of a unit of exit width.

These factors were expected to permit a single-file line flow of 60 persons per unit in level travel and 45 persons on stairs.

In approximately 1988, a significant change in the capacity calculation method was introduced. The unit of exit width was replaced by a system of smaller increments of egress width and capacity. This approach was contained in all of the legacy codes and is contained in the prescriptive provisions of the *International Building Code*, National Fire Protection Association (NFPA) Standard 5000, *Building Construction and Safety Code*® and NFPA 101, *Life Safety Code*®.

The per-person figures are based on the previously used values credited for full units of exit width. The primary difference is that now small increments are considered to add to the capacity of the components of the egress system.

Although Canadian research on egress in tall buildings and larger assembly occupancies has demonstrated the validity of this small increment approach, there was evidence documenting this approach in two very early studies--"Design and Construction of Building Exits" in 1935 and the London Transit Board study in 1958. These two reports show that the small incremental approach was an unsettled issue, even though these reports were thought to support only the unit-width method.

Research has clearly established that crowds do not move in regular files or lanes, especially on stairs where side-by-side body sway almost prevents individuals from walking shoulder to shoulder.

In general the per-person factors for most occupancies are as follows:

- level travel, including ramps .2 inches per person; and
- stair travel .3 inches per person.

For certain occupancies, such as health care and high-hazard areas, more restrictive factors are applied.

In recent years modifications to per-person factors has been permitted for buildings protected throughout by automatic sprinkler protection. This modification allows for greater capacity for the means of egress and is based on the concept that the presence of sprinkler protection will allow more time for safe egress. The concept is not without controversy, since adequate means of egress is critical in situations other than a fire where sprinkler protection is not a factor.

## INDIVIDUAL EGRESS COMPONENT DETAILS

### Minimum Door Width and Clear Opening

Door openings in the means of egress shall be not less than 32 inches in clear width. For new doors, only the width of the doorway, when the door is open 90 degrees, is considered to be the "clear opening."

For existing doors, the clear width is when the door is in the full open position, whether that be 90 degrees or 180 degrees.

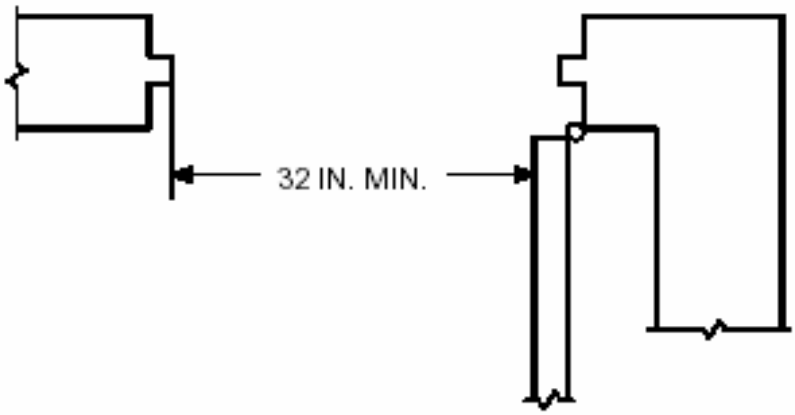


**Figure 4-8**
**Minimum Clear Width of Egress Door**

## Door Swing

In general, doors in the means of egress must swing in the direction of exit travel when the occupant load exceeds 50, or when occupants exit from a hazardous space.

EXIT DOOR SERVING ANY HAZARDOUS AREA
OR
GENERALLY
SERVING AN OCCUPANT LOAD OF 50 OR MORE

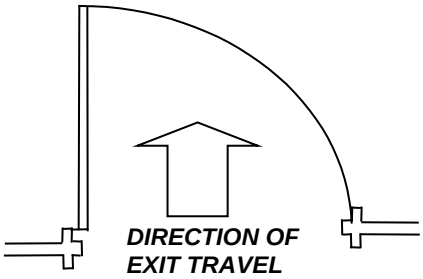


**Figure 4-9**
**Door Swing**

Some very common doors are not generally accepted for use in the normal egress path from a building; however there are exceptions. These include revolving, sliding, and overhead-type doors, which generally are assumed to require special effort to operate.

## Panic Hardware

Panic hardware is not required in all instances for egress from rooms or buildings. It is required, however, in assembly, educational, and institutional occupancies and, usually, whenever the occupant load exceeds 50. If panic hardware is to be installed on any fire-resistive-rated door, it must be listed fire exit hardware. Panic hardware installed on other than fire-rated doors can be listed as exit hardware.

## Travel Distance

The natural path of travel is influenced by the contents and furnishings of each individual building. These items can result in an increase in the length of travel. Good design practice is to recognize the influence these items can have and space exits for a completely open floor at closer intervals than required, thus reducing the possibility of having excessive travel distances once the building is occupied.

Travel distance (actually exit access) is measured on the floor or other walking surface as follows:

- along the centerline of the natural path of travel, beginning from the most remote point subject to occupancy;
- curving around any corners or obstructions with a 12-inch clearance; and/or
- terminating at one of the following: center of the doorway or other point at which exit begins.

When open stairways are permitted as part of the means of egress, the measurement is taken in the plane of the tread nosing.

The travel distance in any occupied space to not less than one exit must be within the allowable distance.

The travel distance to an exit varies with the occupancy and reflects the characteristics of the occupants and occupancy. Allowance generally is provided for increases when complete automatic sprinkler protection is provided.

## Projections

Projections into the corridor space are limited to 3-1/2 inches on each side, or 7 inches on one side of the corridor. A door may not, in its most restrictive position, obstruct more than one-half of the required width of the corridor.

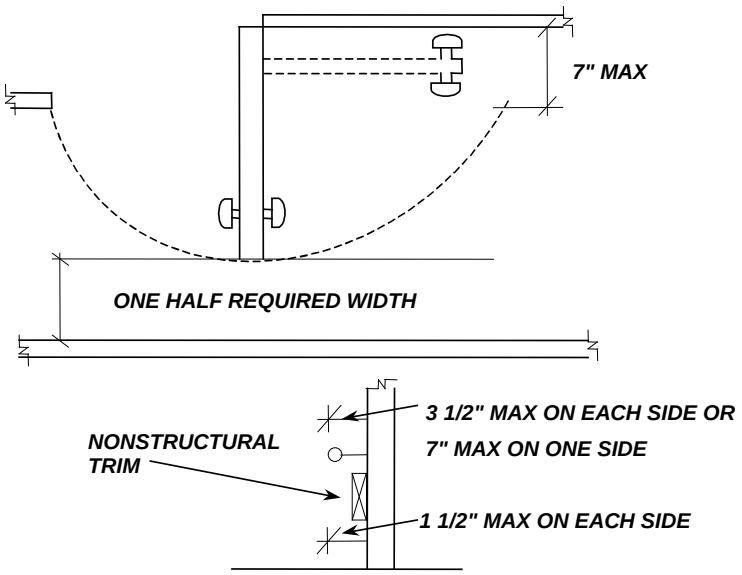


**Figure 4-10**
**Projections**

## Dead End and Common Path of Travel

The terms "dead end" and "common path" often are used interchangeably. Although the concepts are similar, they are actually two clearly different concepts.

A common path of travel exists when a space is arranged such that the occupants within that space are able to travel in only one direction to any of the exits or to reach the point at which occupants have a choice of two paths of travel to remote exits

A dead end is where an occupant enters a corridor or similar space thinking that there is an exit at the end and, finding none, is forced to retrace the path to reach a choice of exits. In general, the maximum length of an acceptable dead end is 20 feet.

## Stairs

The proper design and construction of stairs is critical to the ability of the occupants to use the stairs safely, not only in emergency evacuation, but in everyday use of the structure. Statistics from 1994 to 1998 show that 12,124 individuals died due to falls on stairs/steps. In 1999 alone, 1,029,418 individuals were treated in emergency rooms due to falls on stairs/steps.

The design of stairs, particular the riser and treads was the subject of the 1935 NBS report "Design and Construction of Building Exits." This study found that the dimensions of treads and risers measured indicated that two or three rules customarily used for proportioning risers and treads are adhered to very closely. Risers of 7 or 7-1/2 inches and treads of 10 and 10-1/2 inches far outnumbered any other dimensions. These proportions will be seen to go by the rules that the sum of riser height and tread width shall be not less than 17-1/2 nor more than 18; that the sum of two risers and one tread, in inches, shall be not less than 24, nor more than 25; or that the product of the riser and tread, in inches, shall fall between 70 and 75

This study went on to recommend that treads and risers in exit stairways shall be so proportioned that the sum of the height of two risers, in inches, and the width of one tread, in inches, is not less than 24 nor more than 25; that no riser shall be greater than 7-3/4 inches in height and no tread less than 9 inches in width, exclusive of nosing. Treads shall be not less than 12 inches in width where flights of less than three risers are permitted. Treads less than 10 inches wide shall have nosings. Treads shall be uniform width, and risers uniform height in any one flight. Winders shall not be used in exit stairways.

The true origin of the concept of the sum of the height of two risers and one tread equal between 24 and 25 inches dates back to François Blondel, director of the Royal Academy of Architecture in Paris, who, in about 1672, concluded from personal observation that the normal pace in level walking (24 inches, he said) must be decreased by a regular and fixed amount to allow the foot to be raised in the climbing of stairs.

In the article entitled "The Dimensions of Stairs" published in the October 1974 issue of *Scientific American*, the authors state that Blondel derived a formula stating that the pace must be

decreased by 2 inches for every inch of riser. Expressed mathematically, the formula specified that the depth of the tread should be 24 inches minus two times the height of the riser, or that the total tread and two times the height of the riser should be 24 inches.

The authors go on to state that the apparent anthropometric logic behind Blondel's thesis recommended his formula to generations of architects in spite of the fact that, in stairways where the risers are to be made higher or lower than usual, the rule produces either extremely narrow or extremely wide treads. Moreover, the average human being is bigger now than most people were in the 17th century, and today's inch is shorter that the one employed by Blondel in his calculations. Based on this the authors find it somewhat surprising to find that Blondel's rule or variations of it are still entrenched in many building and fire codes.

The authors conclude in their research that stairs with risers from 4 to 7 inches coupled with treads 11 to 14 inches will result in fairly low rates of energy expended (at normal speeds) and a low rate of missteps.

This research, coupled with an NBS study "An Analysis of the Behavior of Stair Users," ultimately led to the old rule based on two risers and one tread being removed from the *Building Code Handbook*. This requirement was deleted since it was based on a 300-year-old formula in which the inch represented a different unit of measure, and modern research showed the formula to be invalid.

The current design requirements are that risers must be between 4 and 7 inches and treads at least 11 inches.

Consistency in the design and construction of the treads and risers is also very important. There may be not more than 3/16 of an inch variance between the height of any adjacent risers or treads, and the tolerance between the largest and smallest riser in any one flight may not exceed 3/8 inch. Treads and landings are required to be solid, unless a specific exception is noted.

Where the bottom riser adjoins a sloping public way, walk, or driveway having an established grade and serving as a landing, the bottom riser is permitted to have a variation in height or not more than 1 inch in every 12 inches of stairway width.

Landings are required to be at least the width of the stair, measured in the direction of travel. However, in stairs with a straight run, landings do not have to exceed 48 inches.

Minimum headroom generally is accepted as 6 feet, 8 inches measured from the nose of the stair vertically to the lowest projection of the ceiling of the stair.

Barriers at the level of exit discharge must be placed across the stair so that in an emergency people will not continue into the basement or to a level from which they cannot escape.

Signs also must be placed in stairways of buildings four or more stories in height to identify the stairway and to tell occupants from which level they may exit. The codes also say that the sign must tell whether or not the stair has access to the roof.

## Handrails

In order to ensure that the full width of the stairway can be used effectively, handrails must be installed on both sides of the stairs. If the width of the stairway exceeds 75 inches, additional handrails must be provided so that a handrail is within 30 inches of all portions of the required egress width.

Handrails now must be not less than 34 inches and not more than 38 inches above the surface of the tread. This distance is measured vertically to the top of the rail from the leading edge of the tread.

Handrails now must be a minimum of 2-1/4 inches from the wall in order to accommodate a gloved hand.

Handrails must be graspable along their entire length and have a circular cross section with an outside diameter of not less than 1-1/4 inches and not more than 2 inches.

Handrails that are not continuous between flights must extent horizontally at the required height, not less than 12 inches beyond the top riser and continue to slope for one tread beyond the bottom riser.

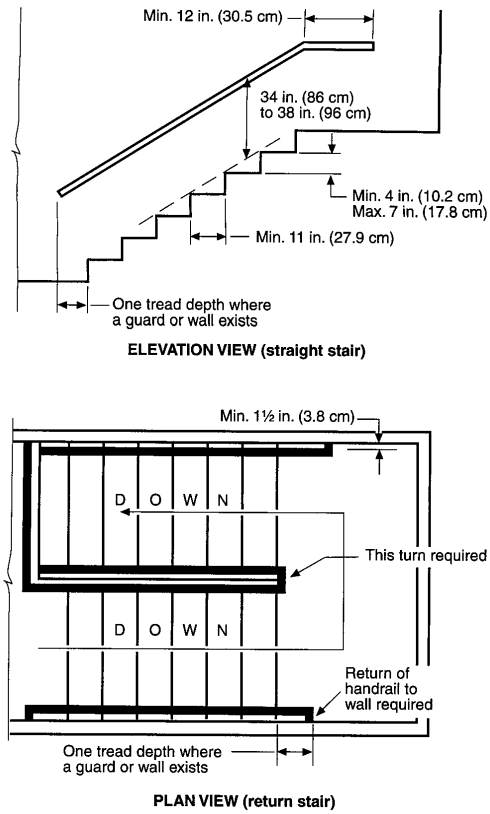


**Figure 4-11**
**Handrails**

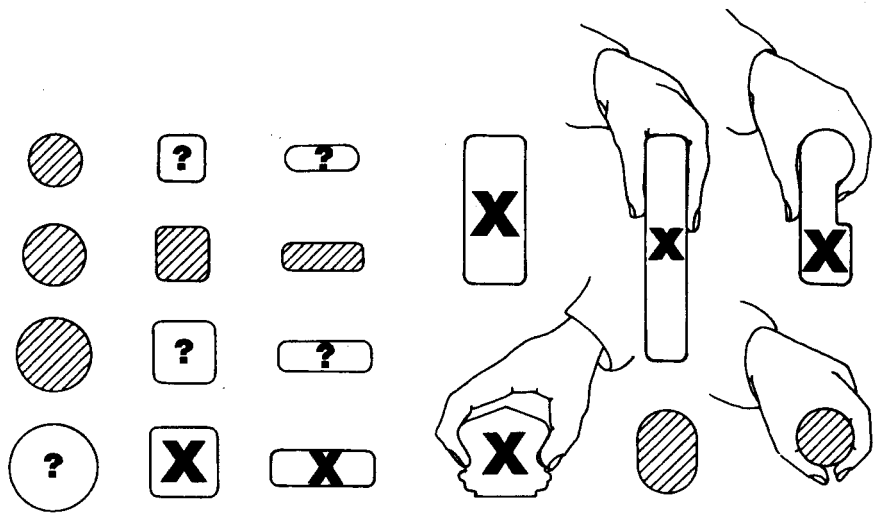

**Figure 4-12**
**Permissible Handrails**

## Stairway Enclosure

When a stairway connects four or more stories, the enclosure must be of 2-hour construction. For stairways that connect three or fewer stories, the minimum enclosure is 1 hour.

Openings into exit enclosures must be limited to exit access to the enclosure from normally occupied spaces. This means that no storage rooms, custodial closets, or mechanical rooms may exit directly into them.

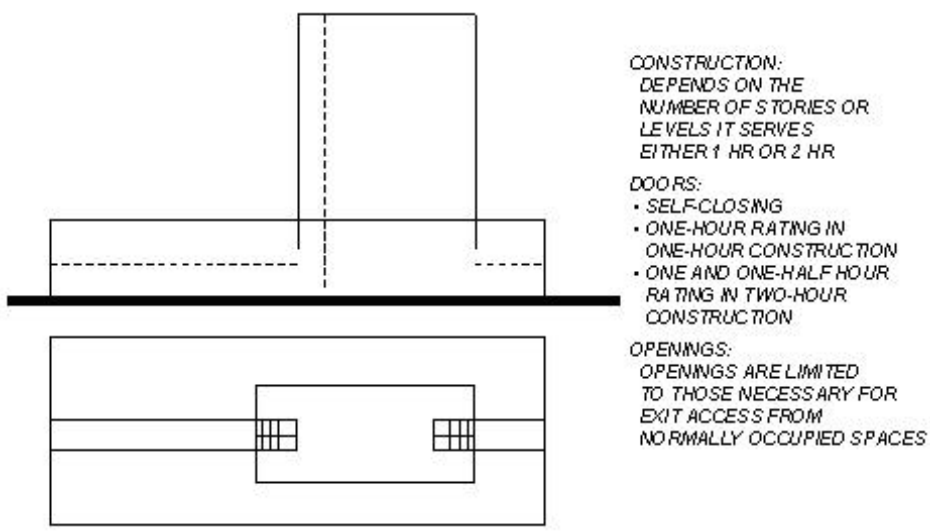


**Figure 4-13**
**Exit Stairway Enclosures**

## Stair (Exit) Discharge

The basic requirement is that all exits must terminate directly at a public way or at an exterior exit discharge. Up to 50 percent of the required exits are permitted to discharge across the level of exit discharge, provided that the level of discharge is protected by an approved automatic sprinkler system.

Stairways also could discharge in an area that is a vestibule or foyer, provided that the depth from the exterior is not more than 120 inches and the length not more than 360 inches. The vestibule or foyer also must be separated from the remainder of the level exit discharge by not less than the equivalent of wired glass in steel frames. The vestibule or foyer serves only as a means of egress and includes an exit directly to the outside.

Stairways also are permitted to discharge into an "exit passageway." An exit passageway is simply an extension of the stair enclosure and extends to the exterior of the building. An exit passageway must meet all of the criteria for stairway enclosure.

## Ramps

Ramps required for the handicapped must not exceed a slope of one-in-twelve and have a walking surface that is slip-resistant.

## Horizontal Exits

Essentially a horizontal exit is an exit from one building into another on the same level. The wall of a horizontal exit must be of 2-hour construction. This separation wall must go through the entire building continuously from the foundation through the roof. The doors that penetrate this wall, as well as any other penetrations, must be of a 1-1/2-hour rating, and must be complete fire assemblies. Note that horizontal exits are not permitted to serve as the only exits from an area, and usually are allowed to function only for up to 50 percent of the required exits. Horizontal exits are designed to protect people when it is not practical to exit completely from the building. You must be certain that the walls forming the horizontal exit are completely without penetrations.

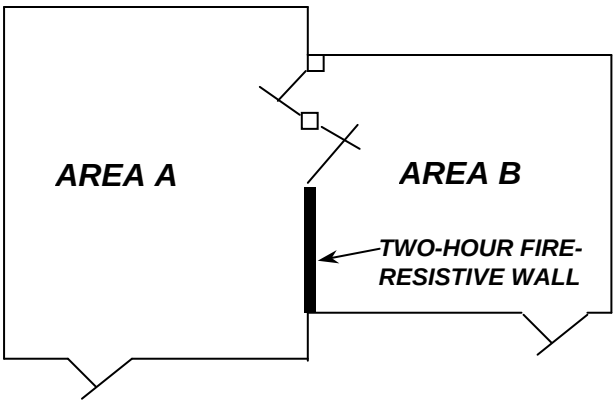


**Figure 4-14**
**Horizontal Exit**

## Corridors

The general rule is that corridors that are used as exit access and serve an occupant load greater than 30 persons must be separated from the remainder of the building by not less than 1-hour-rated construction.

## Illumination

All codes state that the means of egress in a building must be provided with exit illumination. This lighting must provide at least 1 foot of candlelight at the floor. This is about equal to moonlight, which is accepted as that which would be required to permit individuals to exit the building.

## Exit Signage

Signage must be provided at all exits, other than main exits that are obvious and clearly identifiable as exits. Additionally, access to all exits shall be marked by readily visible signs in all cases where the exit or way to the exit is not readily apparent to the occupants. Sign placement shall be such that no point in the exit access corridor is greater than 100 feet from the nearest sign.

Exit signage is required to be located, and of such size, distinctive color, and design, that it is readily visible and shall provide contrast with decorations, interior finish, or other signs.

No decorations, furnishings, or equipment that impairs the visibility of a sign is permitted. No brightly illuminated sign, display, or object in or near the line of vision of the required exit sign that could detract attention from the exit sign is permitted.

Signs must be illuminated. Such illumination can be external, internal, or photoluminescent.

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# Activity 4.3

## Assessing Means of Egress Components

### Purpose

To identify how individual egress components have been compromised.

### Directions

1. You will review a series of photographs.
2. Each photograph contains one or more egress components that has/have been compromised.
3. Identify the means of egress component, and identify the problem in the photograph.
4. Be prepared to discuss findings and possible corrections.

### Photograph

1. _____

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2. _____

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3. _____

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4. _____

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5. _____

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6. _____

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7. _____

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18. _____

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19. _____

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20. _____

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# *UNIT 5: ACTIVE AND PASSIVE FIRE PROTECTION SYSTEMS*

***OBJECTIVES***

*The students will:*

1. *Explain the concepts of both active and passive fire protection systems.*
2. *Predict the effects of fire and heat on certain construction materials, e.g., wood, steel, and concrete.*
3. *Describe fire-resistant materials and methods used to resist flame impingement and fire spread.*

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## INTRODUCTION

The understanding and application of active and passive fire protection approaches follows the concept of the Fire Safety Concepts Tree set forth in National Fire Protection Association (NFPA) 550, *Guide to the Fire Safety Concepts Tree* discussed in Unit 1: Introduction and Course Overview.

## THE FIRE SAFETY CONCEPTS TREE

The Fire Safety Concepts Tree illustrates fire protection along three parallel lines: preventing ignition, managing fire development, and protecting the exposed from fire's harmful consequences. As a design tool, the tree can assist the design professional in analyzing the potential impact of a fire in a specific building and assist both the design professional and code official in developing and analyzing means to deal with a fire. Application of this concept can help identify deficiencies in the building's overall fire safety/fire protection plan.

The objectives of the Fire Safety Concepts Tree are broken down as follows:

- **Preventing fire**: Selecting materials that are appropriate for the building's use, and separating combustible materials from potential ignition sources. This category includes controlling ignition sources, controlling fuel properties, and maintaining separation of fuel and ignition sources.

- **Managing fire**: Ensuring continuous operation and performance of the building's functions should a fire occur. This includes support for firefighters, automatic suppression and detection systems, fire control by construction, smoke control by construction or special equipment, and regulating building contents.

- **Protection of exposed**: Safeguarding occupants and neighboring buildings as well as their operations and contents. This area would include fire-related occupant information, providing and identifying egress routes, refuge provisions, and accommodating the needs of special populations.

## PASSIVE FIRE PROTECTION SYSTEMS

In simple terms, passive fire protection systems are components of a building designed to have a certain degree of fire resistance. These elements of a building must be able to support their structural loads during a fire, contain the spread of smoke and fire gases, and prevent excessive heat flow for a reasonable period of time. These components include fire- or smoke-rated walls, barriers, partitions, floor/ceiling, and roof/ceiling assemblies.

Passive fire protection features may be incorporated into the structural components of the building and/or may be used to provide separations such as those used for hazardous areas, vertical shafts, stairways, tenant/occupancy separations, or smoke barriers.

The selection of building materials and the design of the construction details play an important role in building and occupant fire safety. Two considerations are

- protecting the structural frame to avoid collapse; and
- employing barriers to prevent heat and flame spread to adjacent spaces.

Structural collapse potential and fire endurance of beams, girders, and columns that comprise the structure's frame were determined by the American Society for Testing and Materials (ASTM) using the Standard Time/Temperature Curve (STTC); by fire-resistance tests established in 1918 by the NFPA; and by fire-resistance ratings, which commonly are referenced as:

- 15 minutes;
- 30 minutes;
- 45 minutes;
- 1 hour;
- 1-1/2 hours;
- 2 hours;
- 3 hours; and
- 4 hours.

Fire-resistance ratings of various building components and assemblies are established by exposure in controlled laboratory conditions to a test fire that conforms to the STTC. A 1-hour rating indicates that the assembly of structural elements and protective coverings withstood the standard test under controlled conditions for 1 hour or longer, a 2-hour-rating indicates the assembly withstood a 2-hour or longer test without failure of a critical element. Failure criteria are specific and may include

- failure to support imposed structural loads;
- temperature increase on the unexposed surface (the side opposite the heat source) 250 °F (121 °C) above ambient;
- passage of heat or flame through the assembly sufficient to ignite cotton waste on the side opposite the heat source;
- excess temperature on steel members causing undue weakening; and/or
- failure to withstand attack by fire department hose streams (walls and partitions).

The STTC was adopted by the ASTM in 1918. After adoption by ASTM, the National Bureau of Standards (NBS)--now known as the National Institute of Standards and Technology (NIST)--conducted several full-scale burn tests in the late 1920s to establish how actual building fires compared with the STTC. The testing methods and STTC are contained in NFPA 251, *Standard Methods of Tests of Fire Resistance of Building Construction and Material*, also known as ASTM Standard E119.

The STTC reflects the heat that would be produced by a fire load using ordinary combustibles of about 10 pounds per square foot (psf)/hour of test. In general, if the test specimen withstands fire exposure for a certain time period, supports the applied load (for load-bearing assemblies), does not allow flames or hot gases to ignite cotton waste in contact with the unexposed side, and,

in certain cases, withstands a hose stream test, then it receives a fire-resistance rating. Additionally the assembly may be required to prevent the average surface temperature, measured on the unexposed side, from exceeding 250 °F above its initial temperature or 352 °F (178 °C) rise at any one point.

If the assembly contains steel components, the performance criteria require that certain temperature levels not be exceeded during the testing period. For columns, the temperature is measured at four points, and at no time during the test can the temperature at any one point exceed 1,200 °F (649 °C), and the average temperature cannot exceed 1,000 °F (538 °C). In floor and roof assemblies the temperature is measured again at four separate points, and at no time during the test can the temperature of the steel at any one point exceed 1,300 °F (704 °C), and the average temperature cannot exceed 1,100 °F (593 °C).

The test results are expressed in terms of the time of fire exposure during the test (i.e., 1/2 hour, 1 hour, 2 hours, etc.), and the assembly must not suffer any of the failure criteria described above.

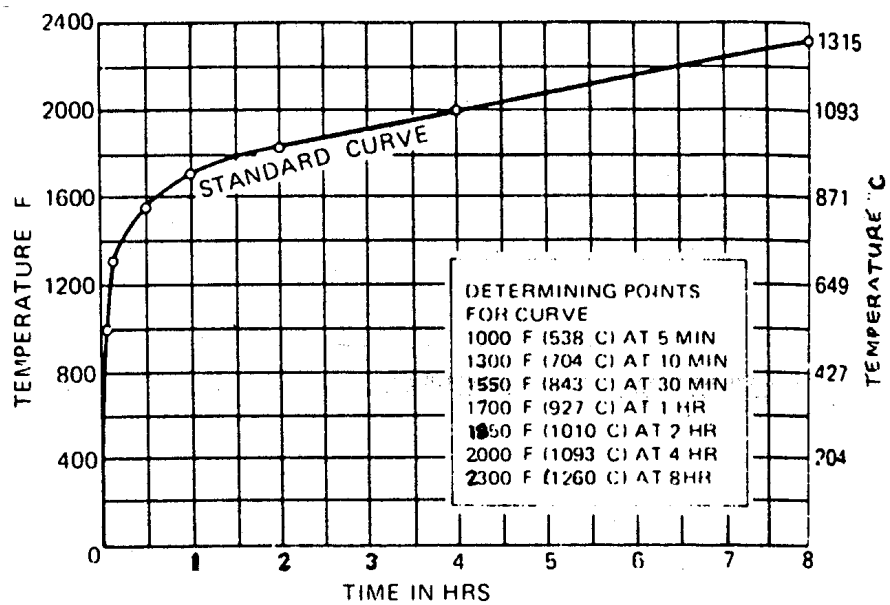


**Figure 5-1**
**The Standard Time/Temperature Curve**

Given that the STTC was established in 1918, serious questions have arisen concerning the validity of continuing to use the original STTC as the basis for a considerable number of the fire-resistance requirements and life safety codes.

There can be no doubt that construction methods and materials, as well as the contents of structures, have changed over time, resulting in greatly increased fire loading and fire severity. In *An Introduction to Fire Dynamics*, author Dougal Drysdale said,

> the empirical data on which the method is based were obtained from full-scale fires in old buildings of traditional design and construction and may not be relevant to modern lightweight constructions…given that in addition synthetic materials burn more rapidly than wood, thereby generating high temperatures more quickly, this approach to fire resistance may no longer be applicable in the present day.

## Fire Testing Standards

In evaluating assemblies and elements for a structure's fire safety, a variety of tests have been accepted nationally as reasonable criteria by which to judge performance. When structural fire resistance is required, the method of protection must be either "a tested and listed assembly" or comply with the provisions of "calculated fire resistance."

Tested and listed assemblies are products that have been subjected to fire performance tests and passed. Test results are published in list form in various directories such as those published by Underwriters Laboratories (UL), the Gypsum Association, or Factor Mutual (FM) Global.

Some of these tests are

- E-119: Rated Assemblies;
- E-152: Doors;
- E-163: Glazing;
- E-814: Penetrations of Rated Walls Needing Fire Stopping;
- UL 555: Fire Dampers;
- UL 555S: Smoke Dampers; and
- UL 555C: Corridor Dampers.

FM Global differs from UL and the Gypsum Association in that they test and **approve** assemblies, specific equipment, or materials. While many of the test standards are the same as those used by UL and the Gypsum Association, there are instances where FM uses more stringent testing criteria because these materials/assemblies are being approved for use in buildings insured under the FM Global insurance organizations.

The Gypsum Association *Fire Resistance Design Manual* contains various assemblies, using gypsum products, which have been tested and listed for use as fire-rated assemblies:

- walls and interior partitions;
- chase walls;
- movable office partitions;
- shaft walls;
- exterior walls;
- metal-clad exterior wall;
- area (party or firewalls) separation walls;
- floor-ceiling assemblies;

- columns; and
- beams, girders, and trusses.

Many design professionals prefer to use the Gypsum Manual because it is the clearest and easiest to use.

### Calculated Fire Resistance

While the most common approach is to use a tested and listed assembly from one of the recognized directories, all of the building codes permit the use of calculated fire resistance. Provisions of the building codes permit the mathematical calculation of the degree of fire resistance based on the type of material used and their fire-resistant properties. Calculations are provided for various protected steel components, concrete, and even wood frame. Tables are provided for wood frame that assign a fire-resistance value to each component of a wall.

Regardless of how the fire resistance is obtained, the design professional must provide to the code official either a design number or the calculations based on specific code provisions.

## BASIC STRUCTURAL BUILDING MATERIALS

### Steel

The popularity of steel-frame building construction is due to its high strength, ease of fabrication, and assured uniformity of quality. Exposed structural steel is vulnerable to fire damage and structural collapse. Fire protection generally is provided for steel by:

- encasing the members in concrete, lath, and plaster, and/or sprayed fibers; and
- installing a ceiling membrane barrier such as tiles in a grid system.

The intensity of stress in a steel member influences the load-carrying capacity. The higher the load stress, the more quickly a member will fail at elevated temperatures. Laboratory fire testing standards for steel use 1,000 °F as the point of test failure. A temperature of 1,100 °F normally is considered to be the critical temperature at which failure begins in the built environment. At 1,100 °F steel has lost 60 percent of its carrying capacity compared to its carrying capacity at room temperatures (60 percent capacity is normally used as the design working stress). If the ends of a structural member are restrained by perpendicular elements, expansion due to heat under load can cause rapid collapse. Fifty feet of steel heated uniformly over its length from 721 to 972 °F (383 to 522 °C) expands 3.9 inches. A heated steel beam restrained by a tilt-up concrete wall could expand enough to push the wall to collapse.

### Reinforced Concrete

Steel-reinforced concrete is another popular building material for strength and fire resistance. Building codes require this material for many tall or critical buildings. Steel is added to concrete to provide additional structural strength.

Although collapse of reinforced concrete structures is rare, loss in strength and damaging effects do occur. Factors that influence strength reduction are

- aggregate type used in the concrete mix;
- moisture content of the concrete;
- type of loading imposed on structural elements, especially beams; and
- level of stress due to loads and attacking elements, such as fire.

The greatest fire problem of prestressed concrete relates to the elevated temperature of the stressed steel encased in the concrete. Elasticity is reduced by 20 percent when the temperature of the steel reaches 600 °F (316 °C). Prestressed wires are permanently weakened when they reach 800 °F (427 °C).

### Wood

Depending on its form, wood may or may not provide reasonable structural integrity in a fire. Factors affecting wood's performance are

- physical size of the structural elements;
- species and moisture content of the material; and
- fire exposure to unprotected, combustible materials.

Fire-retardant treatment delays ignition and retards combustion; however, all wood will burn. Fire-retardant treatment does **not** make wood noncombustible. Burning wood produces charcoal. The charcoal initially provides a protective coating that insulates the unburned wood. Thicker members provide much more structural integrity over the period of fire exposure than do thin ones. Heavy timber has proved to be an excellent form of construction. Wood frame uses structural members smaller than heavy-timber construction, and, when exposed to fire, it offers relatively little structural integrity.

## BUILDING CODE CONSTRUCTION TYPE CLASSIFICATIONS

The various building codes have established various construction types. The following chart provides a cross reference between the various codes. Each of the codes contains narrative descriptions of each type, which can be correlated to the more traditional descriptors: fire resistive, noncombustible, ordinary, heavy timber, and wood frame.

| NFPA 220 NFPA 5000 | I (443) | I (332) | II (222) | II (111) | II (000) | III (211) | III (200) | IV(2HH) | V (111) | V (000) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | |
| **IBC** | N/A | 1A | 1B | IIA | IIB | IIIA | IIIB | IV | VA | VB |
| | | | | | | | | | | |
| **UBC** | N/A | I FR | II FR | II-1 hr | II N | III-1 hr | III N | IV HT | V 1-hr | V-N |
| | | | | | | | | | | |
| **BNBC** | 1A | 1B | 2A | 2B | 2C | 3A | 3B | 4 | 5A | 5B |
| | | | | | | | | | | |
| **SBC*** | I | II | _ | IV 1-hr | IV unp† | V 1-hr | V unp | III | VI 1-hr | VI unp |

*"N" means "nonrated," having no fire-resistant elements.
† Unprotected (unp) refers to passive fire protection/fire resistance, and does not refer to automatic sprinkler protection.

**Figure 5-2**
**Codes and Construction Types**

## Fire Resistive

In fire-resistive construction the structural members are noncombustible and must be protected from fire as specified in the building code. There usually are two subtypes, with the distinction being the level of fire protection required for the specific elements of the structural frame. Only noncombustible materials or limited combustible materials are permitted. An example of limited combustible materials is gypsum board. A building having no exposed structural steel and all vertical openings protected with adequately rated fire assemblies would be classified as fire resistive. Structural steel often is protected by encasing, sprayed-on protection, or membrane ceilings. The bearing walls may be steel with an applied fire-resistive covering. Exterior walls generally are curtain walls and not part of the load-bearing structure. Exterior or interior nonbearing walls have varying degrees of fire resistance. Exit stairs must be enclosed by fire-resistive materials. Roof construction may be similar to that used for floors.

## Noncombustible Construction

In noncombustible construction most components are steel, which provides a totally noncombustible building in which the structural elements may be exposed to the effects of fire. Totally noncombustible refers only to **structural** materials, not to interior finish and contents.

The building's structural framework is made of steel that is bolted, riveted, or welded together. During a fire, exposed steel is susceptible to expansion, distortion, or relaxation of steel members resulting in early collapse. Wall enclosures may be masonry, steel, aluminum, glass, or other material. Once wall coverings are in place, it may be difficult to determine if structural elements are exposed or protected. Concrete construction also can be considered noncombustible. The floor and roof support system often will be lightweight bar joists, trusses, or other lightweight steel.

## Ordinary

In ordinary construction, all or part of the interior structural elements may be combustible. This category is usually divided into **protected** and **unprotected** subtypes, describing the level of fire protection applied to the structure. The building will have masonry exterior walls (usually brick), and wooden structural members and interior construction. Exterior must be noncombustible. The exterior may be required to have a fire-resistance rating, depending on the horizontal separation from nearby properties.

Ordinary construction buildings--often called "Main Street USA"--generally do not exceed six stories, and most often are two or three stories in height. Floor and roof supports are usually wood, but other materials such as steel bar joists may be found. Floor and roof decking most frequently are wooden boards, tongue-and-groove boards, plywood, or composition board. Common walls between buildings may share wall sockets for floor joists and roof rafters.

## Heavy Timber

In heavy-timber construction structural members--columns, beams, arches, floors, and roofs--are unprotected wood with large cross-sectional areas. The sheer mass of wood provides its fire resistance. These buildings consist of masonry (noncombustible) exterior walls and structural members of substantial timber construction. Concealed spaces usually are not permitted.

Minimum dimension of structural wood supports is 8 inches for columns, beams, girders, and arches. All exposed wood has a minimum dimension of 2 inches. This is commonly found in older factories and mills. Wood floors generally are at least 3 inches thick. Roof supports will be wood with minimum dimensions of 4 by 6 inches, and a minimum roof decking thickness of 1-1/8 inches.

## Wood Frame

Wood-frame construction uses structural members entirely of wood. Walls, floors, and roof structure are of wood framing. Usually wood frame is subdivided into two types:

- protected: structural elements protected by fire-resistant materials as required; and
- unprotected: no fire protection requirement.

There are several subcategories of wood-frame construction: post and beam, balloon frame and platform frame. **Post-and-beam** construction has a frame of substantial dimension wood and is sided with a lightweight covering such as wood boards. The construction is commonly used for barns, sheds, and storage buildings, but also may be used in dwellings and other occupancies. In **balloon-frame** construction, studs run from the foundation to the attic. This was used extensively in many parts of the country until the late 1930s for residential and light commercial buildings. Floor joists are tied into the wall, allowing for fire extension in any direction. Fire stopping was not a common practice.

In **platform-frame** construction, the walls of each successive story are built on a platform formed by the preceding floor. The joists for the deck may be full-dimension lumber or of lightweight construction. Once the floor/deck is in place, walls are placed on it with a sill at the bottom of the wall and a plate at the top. Platform-frame construction provides a natural fire barrier for vertical extension within walls. Openings in walls for water, sewer, ventilation, or heating/air conditioning pipes can create voids for fire extension. Noncombustible veneer (brick) on the exterior of a wood-frame structure does not change its classification for fire resistance.

A structure constructed of metal studs and/or metal roof/floor trusses/joists, in which combustible materials are used for structural purposes, also is classified as "wood frame."

## COMPARTMENTALIZATION

Compartmentalization is an application of the concept of passive fire protection; it may consist of firewalls, fire partitions, or horizontal floor/ceiling assemblies with fire-resistive characteristics.

The purpose of compartmentalization is to help confine a fire to a limited portion of a building. When all elements of the compartment are designed, constructed, and maintained successfully, compartmentalization is an effective method of minimizing fire spread, the second strategy of the Fire Safety Concepts Tree.

While both firewalls and fire partitions have fire-resistance ratings, there is a dramatic difference in the required performance of the walls under fire conditions. Firewalls are required to be able to withstand collapse of the building/structure on either side of the wall without collapse of the wall itself. Fire partitions, on the other hand, do not have this structural stability requirement.

In order for passive fire protection features to be effective, they must be designed, constructed, and maintained properly. All penetrations in fire-rated assemblies must be sealed properly, or heat, flame, and toxic gases will escape the compartment. In the past, the codes did not provide very specific requirements for penetration sealing, and this resulted in the use of some very questionable methods. All of the current codes require that penetrations be sealed with a listed "through penetration fire stopping" system. There are numerous sealing methods on the market and, like the fire-rated assemblies themselves, the sealing methods must be used in accordance with their listings. For small penetrations, caulking materials are popular; for larger openings, fire-resistive "pillows" may be employed.

Door and access openings into passive fire-protection barriers, such as exit enclosures and hazardous area separations, also must be protected with rated assemblies. The required rating of the door assembly is established by the rating of the wall being penetrated. These door assemblies must be self-closing or automatic closing* and self-latching. Door assemblies can be obtained in ratings from 20 minutes to 3 hours.

* "Self-closing" doors use closing mechanisms to swing shut as soon as a person passes through. "Automatic closing" doors are held in the open position, and released by smoke detectors or heat-responsive elements.

The hourly rating must not be confused with the A, B, C, D, and E labeling. These alpha designations do **not** indicate a fire-resistance rating; they indicate the type of location in which the door assembly can be used. This designation is established by the provisions of NFPA 80, *Standard for Fire Doors and Other Opening Protectives*, as follows:

| Designation | Use |
|---|---|
| A | Openings in firewalls and in walls that divide a single building into fire areas |
| B | Openings in enclosures of vertical communications through buildings and in 2-hour-rated partitions providing horizontal fire separations |
| C | Openings in walls or partitions between rooms and corridors having a fire-resistance rating of 1 hour or less |
| D | Openings in exterior walls subject to severe fire exposure from the outside of the building |
| E | Openings in exterior walls subject to moderate or light fire exposure from the outside of the building |

**Figure 5-3**
**Ratings of Door Assemblies**

Air-handling systems that penetrate rated assemblies also must be protected with fire dampers to maintain the integrity of the fire barrier.

## Exterior Wall Fire Resistance

Passive fire protection also is used to obtain the fire-resistance ratings of a building's exterior walls. Each of the building codes establishes requirements for the fire ratings of exterior walls based on several factors. All of the codes use the construction type and distance from a property line or assumed property line. All of the codes establish limits on the number of protected or unprotected openings that can be located in such walls. At least two of the model building codes also allow the occupancy classification of the building to be considered in these requirements.

In addition to the requirements in the various building codes, the evaluation of the fire-resistance ratings of exterior walls can be calculated using the provisions of NFPA 80A, *Recommended Practice for Protection of Buildings from Exterior Fire Exposures*.

The provisions of the various building codes and NFPA 80A establish "setback" requirements, and use the setback distance in determining the fire-resistance ratings of exterior walls. Setback requirements generally are established on the local level through zoning or land-use ordinances.

## ACTIVE FIRE PROTECTION FEATURES

Active fire protection refers to those systems that activate in some fashion during a fire to control or mediate the fire or its effects. Active fire protection systems include fire alarm systems, automatic fire sprinkler systems, special hazard extinguishing systems, standpipe systems, and smoke-control/management systems.

### Automatic Sprinkler Protection

Automatic sprinkler systems are the most commonly installed automatic fire suppression systems. The system consists of automatic sprinklers, devices that operate at a predetermined temperature and automatically distribute water on a fire in sufficient quantity at least to contain, and possibly to extinguish, the fire. The water is fed to the sprinklers through a system of overhead piping supplied by some reliable public or private water source.

Despite common television and movie depictions, automatic sprinkler systems do not operate when someone lights a cigarette, nor do all sprinklers operate simultaneously spraying water and damaging property. Except for highly specialized deluge systems, only those individual sprinklers that are heated to their operating temperature will discharge water.

Sprinkler systems have two main purposes: to extinguish unwanted fires, and to control the size of a fire until trained fire-suppression crews arrive to extinguish the fire. Either of these activities results in increased property protection and life safety. When connected to an approved fire alarm system, sprinkler systems provide the added benefit of acting as initiating devices to activate the fire alarm system.

### Sprinkler System Types

The major classifications of automatic sprinkler systems are defined in NFPA 13, *Standard for the Installation of Sprinkler Systems* as:

- Wet-pipe systems use closed automatic sprinklers attached to a piping system containing water under pressure at all times. The wet-pipe system is the most common type of sprinkler system and generally is used unless there is danger of the water in the pipes freezing or when other special conditions require one of the other types of systems.

- Dry-pipe systems employ closed automatic sprinklers attached to a piping system which contains air or nitrogen under pressure. When a fire occurs and an automatic sprinkler activates, the air or nitrogen is released, reducing the pressure in the system to a point at which the pressure on the water supply side causes the valve to operate, allowing water to flow through the system piping. Dry-pipe systems are to be used only in locations that cannot be heated properly.

- Preaction systems employ closed automatic sprinklers attached to a piping system containing air, which may or may not be under pressure. When a fire occurs, a fire-detecting device, such as a smoke or heat detector, activates and causes the water control valve to open and water to flow into the pipe system. Then, when an automatic sprinkler activates, water will be available to flow through the sprinkler immediately. Preaction systems are used commonly in areas where there is danger of serious water damage as a result of a damaged automatic sprinkler or broken piping. Electrical equipment rooms, computer rooms, and operating rooms are locations where preaction sprinkler systems have been used.

- Deluge sprinkler systems employ automatic sprinklers that are open at all times. When a fire occurs, a fire-detecting device, usually a heat detector, activates and causes the deluge valve to open. Water then will flow into the piping and discharge through all the open sprinklers. Deluge sprinkler systems are effective in protecting severe hazards, such as flammable liquids, where there is a possibility that the fire could flash ahead of the operation of closed automatic sprinklers (in this example, a rapid detection system would be required).

## Sprinkler Design Standards

When a sprinkler system is required by code or desired for tradeoffs or other reasons, the following standards are used as appropriate.

- NFPA 13. This standard is the oldest of the sprinkler design standards in use, first published in 1896. Unless allowed by code or by the authority having jurisdiction (AHJ) to use another design standard (see those listed below) NFPA 13 typically is the standard to be used.

- NFPA 13D, *Standard for the Installation of Sprinkler Systems in One- and Two-Family Dwellings and Manufactured Homes.* As the name implies this standard can be used, as permitted, to design systems for one- and two-family dwellings, including manufactured homes. This standard was first adopted by the membership of NFPA at its May 1975 meeting, some 2 years after the NFPA Sprinkler Committee established the Subcommittee on Residential and Light Hazard Occupancies. This document may not be appropriate for use in other types of occupancies.

- NFPA 13R, *Standard for the Installation of Sprinkler Systems in Residential Occupancies up to and Including Four Stories in Height.* This is the latest of the NFPA sprinkler design standards, initially adopted in 1989. This document was produced in an effort to address the gap between NFPA 13 and NFPA 13D. The occupancies for which this design standard is appropriate are indicated by its title.

It also should be noted that, when NFPA 13D and NFPA 13R systems are used, many, if not all, of the normal code modifications are not permitted. Some of the codes do allow limited increases in the height of building when a NFPA 13R system is used.

## Standpipe Systems

Standpipe and hose systems are installed in buildings to facilitate manual suppression by occupants or fire service personnel. Standpipe systems are an arrangement of piping, valves, hose connections, and related equipment installed in a building in a fixed manner. The systems may or may not have hoses permanently attached. Water supplies may or may not be continually provided to standpipe systems.

Fire department personnel trained in manual fire suppression methods are the primary users of standpipe systems. The fixed piping of a standpipe system in a building allows the fire service to connect its hoselines into a pressurized water source near the fire floor. The fire service consequently is relieved of the burden of extending hoses into the building from grade level to the location (floor) of the fire. In mid- to highrise buildings, standpipe systems are extremely important for the prompt manual extinguishment of fires.

## Classes of Standpipe Systems

National standards describe three classes of standpipe systems:

- Class I systems are those systems that have 2-1/2-inch hose connections on the system piping. This size of hose produces what is considered a "heavy fire stream" and is intended primarily for the fire service that supplies its own hoses for fighting the fire.

- Class II systems are those systems that have 1-1/2-inch hose connections. This size of hose is intended primarily for occupant control of a fire until the fire department arrives. A hose is connected to the system piping and is fitted with a nozzle. Due to safety and training concerns, many standpipe systems no longer have occupant hoselines (1-1/2 inch).

- Class III systems are those systems that provide both 2-1/2-inch and 1-1/2-inch hose connections for use by either the fire service or the building occupants. Typically, the two sizes of hose connections are provided by a 2-1/2-inch connection to the system piping and a 1-1/2-inch reducer connection on the 2-1/2-inch connection. The fire service can remove the reducer easily, thus providing the fire service with the 2-1/2-inch connection it requires for manual suppression. A small hose (1-1/2 inch) and nozzle must be provided for occupant use.

Where required, standpipe systems typically are installed in accordance with the requirements of NFPA 14, *Standard for the Installation of Standpipes and Hose Systems*. If the system is a combined sprinkler-standpipe system, the requirements of NFPA 13 also must be met.

## Fire Alarm and Detection Systems

A properly designed, installed, operated, and maintained fire alarm system can reduce the losses associated with an unwanted fire in any building. These losses include both property and, more importantly, human life. The primary motivation for fire alarm system requirements in building

and fire codes is to provide early notification to building occupants so they can exit the building, and to notify the fire service so it can respond to the fire. In settings such as hospitals, the fire alarm system provides notification to staff so they can respond to the fire emergency (as opposed to evacuating the building). This section will assist in understanding the basic features of fire alarm systems and the inspection of these systems. Fire alarm systems are designed and installed in accordance with NFPA 72, *National Fire Alarm Code®*.

## Basic Fire Alarm System Components

Fire alarm systems commonly have six general components:

1. **Alarm initiating device circuits**. These are the circuits to which **initiating devices** such as smoke detectors, heat detectors, manual pull stations, and water flow alarms are connected. Additionally, many system monitor devices important to the overall fire safety of the building also are connected to initiating circuits. These devices indicate an "abnormal" condition not a fire or "alarm" condition. They are referred to as "supervisory devices." One example would be the valve supervisory switch or tamper switch of a valve controlling the automatic sprinkler system.

2. **Alarm indicating appliance circuits**. Audible and visible **alarm indicating** appliances are connected to these circuits to provide warning to the building occupants. Devices that send a signal off-premises also can be connected to these circuits.

3. The **fire alarm control panel** (FACP) contains the electronics that supervise and monitor the fire alarm system. The initiating and indicating circuits are connected directly into this panel.

4. The **primary electrical supply** powers the entire fire alarm system. Primary power for fire alarm systems typically is provided by connecting into the local commercial power service.

5. A **secondary**, or backup, power supply is required so that fire alarm operation can continue if the main power supply fails. The secondary power supply should activate automatically within 30 seconds of the primary power failure to maintain the fire alarm system's normal operating voltage. Secondary power supplies must be capable of powering the system at maximum load for at least a 24-hour period and then be capable of operating all alarm appliances for another 5 minutes. Longer time periods are required for voice-alarm-type systems. Batteries with chargers are a common form of secondary power supply, and engine-driven generators also are acceptable.

6. An important feature of any fire alarm system is the **trouble signal**. Upon the detection of an abnormal condition within the fire alarm system, the trouble alarm signal is activated to attract attention to the system so repairs can be made. NFPA 72 requires that all systems provide an abnormal condition trouble signal for a signal open or ground fault of the system's initiating, indicating circuits, and loss of primary power supply to the system.

All components of fire alarm systems should be listed for fire alarm system use by an acceptable testing agency such as UL. Additionally, all components must be used only for the specific function for which they have been designed and tested (by UL).

A fire alarm panel also can perform functions as needed or required. Examples of these would be to control a remote annunciator or operate relays that capture and recall elevators.

Systems can have an emergency voice/alarm communication system included. Inclusion of this equipment within the fire alarm system provides for the transmission of information to occupants of the building. The fire department also can use this equipment while operating within the building.

## Types of Signaling Systems

A **local protective signaling system** is a type of fire alarm that is contained entirely within the building it services. The main purpose of this type of system is to provide an evacuation alarm for occupants of that building. The system need not be connected by any means to the fire service. Therefore, notification of the fire service can occur only if someone hearing the evacuation alarm calls and reports the fire alarm.

A **central station protective signaling system** is a type of system that has the fire alarm system connected to a privately owned alarm receiving station. The central station monitors the fire alarm system and takes the necessary action when an alarm is received, such as to call the local fire department to report an activated fire alarm. When offsite monitoring of a fire alarm system is required, many codes and code officials require that the monitoring be done by a UL-listed central station.

A **remote station protective signaling system** uses leased telephone lines to connect the fire alarm system of a given building to a remote receiving station such as the local fire or police station.

A **proprietary protective signaling system** is similar to the central station system listed above with the exception that, in this case, the central station is owned by the same concern as the building being monitored. The building(s) being protected may or may not be on the same property as the central station. Many large facilities use this type of system with the security center serving as the central station. College campuses, for example, may have all their buildings' fire alarms report to a security station on site.

An **auxiliary protective signaling system** is connected to a municipal coded fire alarm box dedicated to that building. Upon activation of the fire alarm within the building, the municipal box is tripped and sends a signal to the fire service. It uses the same line as the street fire alarm boxes that are available to the public. Fewer and fewer communities use this method of emergency reporting.

## Types of Initiating Devices

Initiating devices fall into one of two main categories: those that detect a fire, or those that supervise conditions of other related fire protection equipment.

Fire detection can be accomplished by using any device that responds to conditions caused by fire. The most common conditions of fire are heat, smoke, flame, and fire gases.

In addition, people can detect a fire and initiate an alarm by activating a manual pull station. Also, when a sprinkler system activates and causes an alarm, it is a result of the sprinkler system detecting heat produced by the fire.

## Heat Detectors

Heat detectors are used commonly for the detection of fires. Heat detectors are not so prone to false alarms and are less expensive than smoke detectors. However, heat detector response may not be adequate in many instances, thus precluding their use. Heat detectors are **not** considered life safety devices; they are slower to respond to fires than smoke detectors. Heat detectors typically are best suited for detecting fast-growing fires in small spaces. They are also a means of fire detection in locations that cannot be protected by smoke detectors due to such environmental effects as mist, normally occurring smoke, and high humidity.

## Smoke Detectors

The benefits of smoke detectors cannot be overemphasized. However, smoke detectors are not useable in all environments, and their effectiveness varies depending on the fire scenario and occupant capability. The two basic operating mechanisms used in current smoke detectors are photoelectric and ionization.

**Ionization smoke detectors** have a small amount of a radioactive material located within the detector that ionizes the air entering the detection chamber. Once ionized, the air particles become conductive, allowing a current to flow through the detector circuitry. Smoke entering the ionization chamber causes a reduction in the current flowing through the detector's circuitry. At a certain reduced level of current flow, the detector signals an alarm.

**Photoelectric smoke detectors** use one of two methods to detect smoke; however, both have the basic components of a **light-emitting source** and a **receiver**.

Photoelectric smoke detectors that operate on the light obscuration principle work as follows: A light source is directed at a receiver that is accustomed to receiving a certain intensity of light. When smoke particles enter the detection chamber they partially block the light traveling from the emitter to the receiver. When the light reaching it is reduced or obscured by a certain amount, an alarm is generated by the detector's built-in circuitry.

The second operating principle used in photoelectric detectors is that of light scattering, which is more common and which operates as follows: The receiver in the detection chamber is located so that the light emitted normally is not "seen" by the receiver. That is, the light emitter and receiver are not aligned as with the light obscuration method. When smoke enters the detection chamber it is struck by light from the emitter. A fraction of the light striking the smoke particles is scattered or "reflected" away from the smoke particle. Some of this scattered light lands on, or strikes, the photo receiver. When a preset amount of light lands on the receiver, the detector signals an alarm.

## Suitability

Detectors that operate on the photoelectric principle generally are recommended for use in locations where slow-growing, smoldering fires are expected. These fires typically generate large-size particles, 0.3 to 10 microns. They also respond better to light gray smoke as opposed to very dark smoke. Ionization-type detectors respond better to fast-flowing, flaming fires that produce smaller particles, 0.01 to 3.0 microns. Ionization detectors respond better to dark smoke than to light smoke. Photoelectric detectors are better suited than ionization detectors for locations where the humidity is high. Air velocity also may affect smoke detector operation.

## Pull Stations

A very common initiating device, the manual fire alarm box, usually is referred to as a manual pull station. These are simple devices that operate manually, i.e., they require the actions of a person operating the mechanism. These are found throughout building hallways, near exits, and at other strategic locations such as a nurse's station or security center.

## Interconnection with Fire-Suppression Systems

Fire-suppression systems can be connected into a fire alarm panel so that an activation of such a system causes the fire alarm to signal an alarm. Wet-pipe automatic sprinkler systems are commonly fitted with water flow detectors. As water starts to flow in the sprinkler piping it causes a vane to swing into an alarm position; this sends an alarm to the fire alarm panel. Dry-pipe sprinkler systems can be fitted with pressure sensors for the same reason. All other fire-suppression systems also can be connected to the fire alarm panel.

Not all devices signal an emergency alarm condition. Many devices can be connected to the fire alarm system so that they can be monitored for abnormal conditions. Perhaps the most common example is that of a valve supervisory switch or "tamper switch" on a sprinkler system. To ensure valves that control a sprinkler system are in the proper position, they can be fitted with a tamper switch that will operate if the valve position is altered. If the valve is moved, a signal will be given at the fire alarm panel indicating the valve should be inspected. This is important since someone could, inadvertently or intentionally, close a valve on the sprinkler system rendering the system inoperable.

Many other indicating devices can be connected into the fire alarm panel for supervision. The following is a partial list provided for information purposes:

- water level and temperature in a gravity tank;
- water level and air pressure in storage tank;
- status of fire pump;
- air pressure on dry-pipe system; and
- temperature in wet-valve room.

## Occupant Notification

For occupants of a building to be aware of a possible fire emergency in a building they must be notified in some manner. Fire alarm systems typically accomplish this through the use of audible and visible indicating devices. Both types of signals should be used so that occupants don't mistake the signals' purpose, and because the building may be occupied by handicapped persons. For example, a profoundly deaf person will not hear a fire alarm bell, and a blind person cannot see a fire alarm strobe light.

Bells, chimes, horns, buzzers, and speakers as well as strobe lights, rotating beacons, and flashing lights are common examples of these notification devices. Many times the audible devices will ring in what is referred to as "march time." This means the ringing is not constant but in an on-off manner. The purpose of this march-time pattern is to alert occupants that the signal means "fire," and is not to be misunderstood as a security, elevator, refrigeration, or some other alarm. Flashing lights or strobes are better at alerting occupants than a steadily illuminated light. It is common practice, but not always desirable, to locate the audible and visible devices in one unit.

All signaling systems should be engineered and tested to ensure they are capable of alerting all occupants. This requires knowledge of the background noises that can be expected. For example, a mechanical room with equipment operating that produces high noise levels may require special attention.

## Other Functions

Fire alarm systems can do more than receive an indication of an emergency and send an alarm. This section will identify some of the common functions controlled by fire alarm systems. The list is not intended to be all-inclusive.

The fire alarm panel can send a signal to the fire department or other desired facility via one of the methods described at the beginning of this section.

Elevator capture and recall is a common function that fire alarm panels can perform easily. Upon receiving an alarm, the fire alarm panel can operate one or more relays that control the actions of the elevator. The heating, ventilating, and air conditioning system (HVAC) or a smoke-control system also can be controlled through fire alarm panels.

### Annunciators

Remote annunciators frequently are included in fire alarm systems. A remote annunciator "displays" the condition of the fire alarm panel at a remote location--often at a building's main entrance--usually through light-emitting diodes on graphic or tabular displays. Remote annunciators also can be equipped with switches that control the main fire alarm panel. The fire alarm panel may be located in a secure area out of the public way. However, those investigating an alarm need to inspect the indicators on a fire alarm or annunciator panel to determine the cause of the alarm and the location of the initiating device. Remote annunciators can be provided at locations such as the main lobby of a building, or at a security desk so that the needed information on the condition of the fire alarm panel is available readily.

### Fire-Suppression Systems

It was stated previously that fire-suppression systems may be connected to fire alarm panels so that their activation is monitored. Another important function that a fire alarm panel can control is the activation of fire-suppression systems. In this function, the fire alarm panel identifies a fire through its initiating circuits, and activates a fire-suppression system such as a clean agent, Halon, dry chemical, or carbon dioxide system. This means that fire alarm systems are capable of both alerting when a fire-suppression system is activated and acting as a control mechanism when suppression systems are activated. Other types of fire-suppression systems that fire alarm panels can control are pre-action and deluge sprinkler systems, which were discussed previously.

## SMOKE CONTROL

All fires produce smoke that, if not controlled, will spread throughout the building or portions of the building, endangering life and damaging property. Smoke and other toxic gases produced by a fire are the leading killers in these events. Smoke-control systems are designed to inhibit the flow of smoke into means of egress, exit passageways, or other similar areas of a building.

Smoke-control systems should be engineered for the specific occupancy and building design. Additionally, the smoke-control system design should be coordinated with other life safety systems so that they complement, rather than counteract, each other.

Such systems are intended to control the migration of smoke to maintain tenable conditions in protected areas, but it should not be expected that such areas would be completely free of smoke.

The purpose is to accomplish one or more of the following:

- maintain a tenable environment in the means of egress during the time required for evacuation;
- control and reduce the migration of smoke from the fire area;
- provide conditions outside the fire zone that will assist emergency response personnel in conducting search-and-rescue operations and in locating and controlling the fire; and
- contribute to the protection of life and reduction of property loss.

Limiting fire size by providing automatic sprinklers or other means of automatic suppression generally will be necessary for effective and economical control of smoke in most occupancies. Other techniques may be appropriate for specialized occupancies or existing facilities. When smoke-control systems are provided, they should be activated during the early stages of a fire emergency to maintain a tenable environment in the area to be protected.

The smoke-control system should be functional during evacuation of the areas protected by the system.

A firefighter's smoke-control station (FSCS) includes monitoring and overriding capability over smoke control systems and equipment provided at designated location(s) within the building for the use of the fire department.

## Smoke-Control Terminology

- **Smoke**: The airborne solid and liquid particulates and gases evolved when a material undergoes pyrolysis or combustion, together with the quantity of air that is entrained or otherwise mixed into the mass.

- **Smoke barrier**: A membrane, either vertical or horizontal, such as a wall, floor, or ceiling assembly, which is designed and constructed to restrict the movement of smoke. A smoke barrier may or may not have a fire-resistance rating. Smoke barriers may have openings protected by closing devices or adequate air flows.

- **Smoke zone**: The building space surrounded by a smoke barrier. The space may occur between floors, or on a single floor with vertical separations constructed to resist smoke movement.

- **Smoke-control system**: A mechanical or gravity system intended to move smoke from the smoke zone to the exterior of the building, including smoke removal, purging, and venting systems, as well as the function of exhaust fans used to reduce the pressure in a smoke zone. Maintenance of a tenable environment in the smoke zone is not within the capability of these systems.

- **Pressurized stair towers**: A type of smoke-control system in which stair shafts are mechanically pressured with outside air to keep smoke from contaminating them during a fire.

- **Stack effect**: The vertical airflow within buildings caused by temperature differences between the building interior and exterior. Once a smoke column loses its upward momentum, the smoke spreads horizontally. This is particularly noticeable in tall buildings.

## Factors Affecting Smoke Control

Frequently, smoke flow follows the overall air movement within a building. Although a fire may be confined within a fire-resistive compartment, smoke can spread readily to adjacent areas through openings such as construction cracks, pipe penetrations, ducts, and open doors. The principal factors that cause smoke to spread to areas outside a compartment are

- the stack effect;
- fire temperature;
- weather conditions, particularly wind and temperature; and
- mechanical air-handing systems.

These factors cause pressure differences across partitions, walls, and floors that can result in the spread of smoke.

Smoke migration can be controlled by altering these pressure differences. Building components and equipment such as walls, floors, doors, dampers, and smoke-proof stair towers can be used along with the HVAC systems to aid smoke control. Proper overall building design and tight construction are essential to smoke control.

## Smoke-Control Principles

Smoke control is based on two principles:

- Air pressure differences of sufficient magnitude acting across barriers will control smoke movement.

- Air flow by itself will control smoke movement, if the average air velocity is adequate.

The preferred means of controlling smoke movement is by creating air pressure differences across partitions, floors, and other building components. The basic concept of building pressurization is to establish a higher pressure in adjacent spaces than in the smoke zone. In this way, air moves into the smoke zone from adjacent areas, and smoke is inhibited from dispersing throughout the building.

Airflow can be used to stop movement through a space. This principle is used most commonly to control smoke movement through open doorways. The flow of air through the opening into the smoke zone must be of sufficient velocity to prevent smoke from leaving that zone through the openings. Since the air quantities required are large, airflow is not the most practical method of controlling smoke movement.

Automatic sprinkler and other suppression systems are an integral part of many fire protection designs, and the reliability and efficiency of such systems in controlling building fires is well documented. It is important to recognize that the functions of both suppression and smoke-control systems are important. Automatic suppression systems can extinguish a fire early in its

growth, thereby eliminating additional smoke generation. On the other hand, well-designed smoke-control systems can maintain a tenable environment along critical egress routes during the time it takes the fire-suppression system or fire service personnel to achieve final extinguishment.

A smoke-control system can have an adverse effect on the performance of gaseous agent (such as clean agent, Halon, carbon dioxide, nitrogen) suppression systems when the systems are located in a common space. Gaseous suppression systems and smoke-control systems cannot perform their intended functions simultaneously when they are located within the same space. In the event that both systems are activated concurrently, the smoke-control system may dilute the gaseous agent in the space. Since gaseous suppression systems commonly provide only one application of the agent, the potential arises for renewed growth of the fire.

## Dedicated Smoke Control

Dedicated smoke-control systems are intended for smoke control only. They are separate air-moving and distribution systems that do not function under normal building operating conditions. Upon activation, these systems operate specifically to perform the smoke-control function.

Dedicated systems have the following advantages:

- Modification of the controls during system maintenance is less likely to occur.
- Operation and control generally are simpler.
- They are less likely to be affected by the modification of other building systems.

They have the following disadvantages:

- They may be more costly.
- Component failures may go uncorrected, since they do not affect normal building operations.
- Systems frequently require more building space.

## Nondedicated Smoke-Control Systems

Nondedicated systems are those that share components with some other system(s) such as the building HVAC system. Activation causes the system to change its mode of operation to achieve the smoke-control objectives.

Nondedicated systems have the following advantages:

- Component failure of equipment required for normal building operations is less likely to remain uncorrected.
- Equipment costs may be lower.
- Additional space for smoke-control equipment may not be necessary.

They have the following disadvantages:

- System control may become elaborate.
- Inadvertent modification of controls affecting smoke-control function is more likely to occur.
- Other system modifications may interfere with smoke-control system operations.

## Smoke-Control System Types

Systems for controlling smoke movement in a building generally can be divided into two separate types: shaft protection and floor protection. Shaft protection can be further divided into stair tower pressurization systems and elevator hoistway systems.

Floor protection encompasses several variations of zoned smoke control. Use of a particular system or combination of systems is dependent on building and fire code requirements, as well as on the specific occupancy and life safety requirements of the situation being considered.

The primary goal of pressurized stair towers is to provide a tenable environment within the stair tower in the event of a building fire. A secondary objective is to provide a staging area for firefighters. On the fire floor, a pressurized stair tower needs to maintain a pressure difference across a closed stair tower door so that smoke infiltration is limited.

Elevator hoistways have been a readily available conduit for movement of smoke throughout buildings in past fires. This is because the elevator doors do not have tight fittings, and elevator hoistways have openings in their tops.

## Air Supplies

- **Noncompensated**: Supply air is injected into the stair tower by actuating a single-speed fan, thus providing one pressure difference with all doors closed, another difference with one door open, and so on.

- **Compensated**: Compensated systems adjust to various combinations of open and closed doors, while maintaining positive-pressure differences across such openings. Systems compensate for changing conditions by either modulating supply airflows or by relieving excess pressure from the stair tower.

The supply air intake should be separated from all building exhausts, outlets from smoke shafts and roof smoke and heat vents, open vents from elevator shafts, and other building openings that might expel smoke from the building in a fire. This separation should be as great as is practically possible.

Because hot smoke rises, consider locating supply air intakes below such critical openings. However, outdoor smoke movement that might result in smoke feedback depends on location of the fire, location of points of smoke leakage from the building, wind speed and direction, and the temperature difference between the smoke and the outside air.

At present, too little information is available about such outdoor smoke movement to warrant general recommendations favoring ground-level intakes rather than roof-level intakes.

- A single-point injection system is one that has pressurization air supplies to the stair tower at one location.

- Single-point injection systems can fail when a few doors are open near the air supply injection point. All of the pressurization air can be lost through these open doors, and the system then will fail to maintain positive pressures across doors further from the injection point.

- Because a ground-level stair tower door is likely to be in the open position much of the time, a single-bottom injection system is especially prone to failure. Consideration of this specific situation, as well as careful design analysis overall, is required for all single-bottom injection systems, and for all other single-point injection systems for stair towers in excess of 100 feet in height.

Multiple-point injection systems can be used to overcome the limitations of single-point injection systems. The pressurization fans can be located at ground level, roof level, or at any location in between.

## Smoke-Control Zones

Some buildings can be divided into a number of smoke-control zones, each zone separated from the others by partitions, floors, and doors that can be closed to inhibit the movement of smoke. A smoke-control zone can consist of one or more floors, or a floor can have more than one smoke-control zone.

Smoke-control zones should be kept as small as practical so that they can be evacuated readily, and so that the quantity of air required to pressurize the surrounding spaces will be kept to a manageable level. However, they should be large enough so that heat buildup from the fire will be diluted with surrounding air sufficiently to prevent failure of major components of the smoke-control system.

## System Activation

Automatic activation (or deactivation) includes all means where a specific fire detection device or combination of devices activates one or more smoke-control systems without manual intervention. For purposes of automatic activation, "fire detection devices" include automatic devices such as smoke detectors, waterflow switches, and heat detectors.

Manual activation (or deactivation) covers all means whereby an authorized person activates one or more smoke-control systems by means of controls provided for that purpose. For purposes of manual activation, the location of the controls may be at a controlled device, at a local control panel, at the building's main control center, or at the firefighter's central control station.

Manual fire alarm pull stations generally should not be used to activate smoke-control systems, other than stair tower pressurization systems, because of the likelihood of a person signaling an alarm from a station outside the smoke zone of fire origin which potentially could draw the smoke from one zone into another.

## Firefighter's Smoke-Control Station

The FSCS, when required, should provide full monitoring and manual control capability over all smoke-control systems and equipment. The FSCS should have the highest priority control over all smoke-control systems and equipment. Where manual controls also are provided at other building locations for control of smoke-control systems, the control mode selection from the FSCS should prevail. The FSCS should contain a building diagram that clearly indicates the type and location of all smoke-control equipment (fans, dampers, etc.), as well as the building areas affected by the equipment. The location of the FSCS is selected by the local fire department.

The actual status of the systems and equipment that are activated or are capable of activation for smoke control should be indicated clearly at the FSCS.

- Automatic activation. Operation of any zone of the building protective signaling system should cause all stair pressurization fans to start. In limited instances, it may be desirable to pressurize only some stair towers due to particular building configurations and conditions. A smoke detector should be provided in the air supply to the pressurized stair tower. Upon detection of smoke, the supply fan(s) should be stopped.

- Manual activation. A manual override switch should be provided at the FSCS to restart the stair tower pressurization fan(s) after shutdown from the smoke detector, should it be determined that a lesser hazard exists from smoke entering the fan than from smoke migrating into the stair tower.

- Manual activation or deactivation of zoned smoke-control systems and equipment should have priority over automatic activation of smoke-control systems and equipment, as well as over all other sources of automatic control within the building.

## Malls, Atria, and Similar Large Spaces

Smoke management systems in malls, atria, and similar large spaces have different goals and objectives than other smoke-control systems. The objective is to provide a method for managing smoke in large-volume, noncompartmentalized spaces.

- maintain a tenable environment in the means of egress from large-volume building spaces during the time required for evacuation;
- control and reduce the migration of smoke between the fire area and adjacent spaces;
- provide conditions within and outside the fire zone that will assist emergency response personnel to conduct search and rescue operations and to locate and control the fire;
- contribute to the protection of life and reduction of property loss; and
- aid in postfire smoke removal.

## Definitions

- **Atrium**: A large-volume space created by a floor opening or series of floor openings connecting two or more stories that is covered at the top of the series of openings and is used for purposes other than an enclosed stairway, elevator hoistway, escalator opening, or utility shaft used for plumbing, electrical, air conditioning, or communication facilities.

- **Communicating space**: Spaces within a building that have an open pathway to a large-volume space such that smoke from a fire in the communicating space can move unimpeded into the large-volume space. Communicating spaces may open directly into the large-volume space or may connect through open passageways.

- **Covered mall**: A large-volume space created by a roofed-over common pedestrian area in a building enclosing a number of tenants and occupancies such as retail stores, drinking establishments, entertainment and amusement facilities, offices, or other similar uses where tenant spaces open onto or directly communicate with the pedestrian area.

- **Large-volume space**: A noncompartmented space, generally two or more stories in height, within which smoke from a fire either in that space or in a communicating space can move or accumulate without restriction. Atria and covered malls are examples of large-volume spaces.

Smoke produced from a fire in a large-volume open space is assumed to be buoyant, rising in a plume above the fire and striking the ceiling or stratifying due to temperature inversion. At this point, the space can be expected to begin to fill with smoke. Makeup air should be provided at a low velocity. For effective smoke management the makeup airflow must be sufficiently diffused so as not to affect the flame or smoke. The rate of makeup air must not exceed the exhaust rate that the atrium or mall achieves, or a positive pressure relative to adjacent spaces. If air enters the smoke layer above the interface it must be accounted for in the exhaust calculations.

Automatic suppression systems are designed to limit fire size and will, therefore, limit smoke generation. Fires in spaces adjacent to atria and covered mall pedestrian areas also can be limited effectively so as to cause minimal effect upon atrium spaces or covered mall pedestrian areas.

Activation of sprinklers near a fire will cause cooling of the smoke, resulting in a loss of buoyancy. This may cause smoke to descend and visibility to be reduced.

### Design Objectives

Design objectives normally will include management of smoke within the large-volume space and any spaces that communicate with the large-volume space. The source of the smoke may be a fire within the large-volume space or within the communicating space. Design objectives should include

- maintain the smoke layer interface to a predetermined elevation;
- maintain a tenable environment on all exit accesses and areas of refuge access paths for a sufficient time to allow all occupants to reach an exit or area of refuge;
- limit the spread of smoke from the fire/smoke zone into other zones that may be exits, exit access routes, areas of refuge, or communicating spaces;
- provide adequate visibility to allow fire department personnel to approach, locate, and extinguish the fire;
- exhaust smoke that has accumulated in the large-volume space within a specified time; and
- limit the smoke layer temperature.

It is not a realistically achievable design objective to prevent accumulation of smoke within the upper portions of a large-volume space under most fire scenarios.

## SUMMARY

Regardless of whether the approach is active or passive or a combination, the code official should give due consideration to the continued maintenance of the systems or components. If the protection cannot be maintained readily, the overall goal of fire safety will not be achieved.

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# *UNIT 6: HAZARDOUS MATERIALS: RECOGNITION AND CONTROL*

### *OBJECTIVES*

*The students will:*

1. *List the 11 categories of hazardous materials regulated by the model building and fire codes, and provide examples of each.*

2. *Explain the difference between physical and health hazard materials.*

3. *List the four basic concepts for hazardous materials control in the built environment.*

4. *Explain how the environment where a material is located affects code enforcement.*

5. *Identify the physical state and hazard classification of a given list of hazardous materials, and provide the source of the information.*

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## HAZARDOUS MATERIALS RECOGNITION AND IDENTIFICATION

In the last generation or so, the fire service and allied professionals have become intimately aware of the presence and hazards of chemicals in their pure, mixed, or compound states. In the 1970s and 1980s, a series of significant transportation disasters emphasized the risks of hazardous materials: liquefied petroleum gas rail cars suffered Boiling Liquid Expanding Vapor Explosions (BLEVEs), tractor-trailer combinations carrying high-powered explosives detontated, and numerous marine emergencies resulted in millions of barrels of petroleum products burned or spilled into the environment.

For years, hazardous material regulations were left to Federal or State agencies, or self-policing by business and industry. At one time, the model fire codes included only five pages of regulations pertaining to hazardous materials, and left it up to the fire code official to interpret the many conflicting rules that existed in Federal and State statutes.

In the 1980s, the fire service initiated a comprehensive effort to regulate hazardous materials in the built environment. The first efforts involved collecting various National Fire Protection Association codes and standards and condensing them into a single chapter of the fire code: that effort was so significant that many fire service professionals felt overwhelmed.

The purpose of this unit is to provide the fire inspector or code official an overview of the fundamental challenges pertaining to hazardous materials regulations, and provide tools for the correct application and interpretation of the model building and fire codes. More comprehensive or detailed training on specific hazardous materials or code sections is available through other courses or organizations.

## HISTORY OF HAZARDOUS MATERIALS DEVELOPMENT

Developed by the Chinese, explosives were the first manufactured hazardous materials. Explosives remained essentially the only bulk hazardous material until the discovery of oil, natural gas, and industrial alcohols. The period from 1880 through 1940 produced some remarkable developments in "miracle" materials, including rubber, nylon, rayon, crude plastic, gasoline, heavy fuel oils, city gas, electricity, radio waves, vacuum tube, high explosives, acids, corrosives, and combustible metals.

From 1940 to the present, a technological explosion of useful new hazardous substances has been, and continues to be, developed for modern society. In the past 70 years we have seen incredible growth in the plastics industry with a move from simple nitrocellulose products to complex multichain organic polymers. We have witnessed toxic and highly toxic chemicals used for beneficial purposes such as pesticides, herbicides and rodenticides; and seen them exploited as weapons of mass destruction. We have observed the growth of convenience products including aerosols that contain both hazardous and inert product and propellant constituents. The incredible popularity of the personal automobile has spawned an entire industry of related products from fuels, lubricants, paints, cleaning supplies, and even deodorizers.

As greater international competition occurs for new energy sources, the presence and application of hazardous materials will increase as well. Biomass products, biodiesel, hydrogen fuel cells, mixed fuels, and the resurgence of nuclear power for electrical generation mean new materials and applications will evolve.

We can't foresee what innovations will bring new hazardous materials into the environment and marketplace. We must remain aware and educated as these materials are introduced into our communities. This brings new challenges to the fire protection professional to assure these materials are manufactured, stored, used, handled, and shipped in ways that protect people and the environment.

## Perceiving the Presence of Hazardous Materials

The first challenge in controlling hazardous materials is perceiving or recognizing their presence. Hazardous materials are common in the normal environment. Some products--such as gasoline that can be purchased at the corner convenience store--are so pervasive in our commerce and environment that they are not perceived by many to be "hazardous." Have you ever seen someone spill gasoline on the ground and act like it's not a problem? As people use a product on a regular basis, and their familiarity grows with it, they may gain a perception that the material is harmless to humans or the environment.

Fire inspectors, code officials and allied professionals are in a challenging position: they often must compel compliance with regulations that many people find inconvenient, burdensome, or even downright silly. Code professionals must be able to identify hazardous materials, understand their risks, and be able to determine where these materials may be found.

One **expects** to find hazardous materials at a chemical manufacturer, but fire protection professionals also must be **aware** of their possible presence in many of the more routine inspection environments. For example:

- Swimming pool supply and "big box" stores will have chlorine, chlorine derivatives, or oxidizers used to treat the water in swimming pools and hot tubs.

- A sewer or water treatment plant also uses chlorine or ozone for water purification.

- There are cryogenic materials and radiation sources in a doctor's office. Liquid nitrogen for removing skin blemishes and x-ray equipment for medical examination are common office products. There also may be flammable liquids in pressurized containers (aerosols) to kill unwanted contaminants on solid surfaces.

- Hospitals also have radiation sources, as well as chemicals found in the laboratories or custodial facilities. Etiological hazardous materials that create short- or long-term ill effects may be found in hospital waste. Medical gases--such as oxygen or nitrous oxide--may have properties that affect fire behavior.

- Retail and "big box" stores will have a variety of flammable and combustible liquids, pesticides, insecticides, heavy metals, and other chemicals.

- Hardware, lawn supply, railroad yards, truck terminals, and manufacturing plants all handle hazardous materials.

## HAZARDOUS MATERIALS LIFE CYCLE

Hazardous materials are processed, stored, handled, transported, and dumped or recycled. At each step in the life cycle of these materials different hazards are created.

First, the material is manufactured or extracted from a natural source. The production may occur at a sophisticated production and processing facility, or may be found in a tinkerer's garage or backyard. Chemicals in their raw state may not be hazardous, but when mixed with others or processed under heat, pressure, electricity, or other means, may become dangerous.

Once the materials are produced, hazardous materials often are shipped or transferred to a facility closer to their point of end use. Shipping can occur in a variety of ways: truck, rail, air, barge, pipeline, etc. The hazards that occur during transportation may include leak, spill, release, explosion, or fire. In most cases, Federal regulations promulgated by the U.S. Department of Transportation (DOT) establish how products will be transported from one facility to another.

Hazardous materials may be shipped to an intermediate destination where they are stored until ready for distribution. They can be stored and/or transferred to smaller vessels for distribution and sale. Similar hazards of leak, spill, release, explosion, or fire can occur during this phase, and generally local first responders are called to deal with the consequences.

Finally, either hazardous materials may be consumed totally, or waste may be generated for disposal (used motor oil, nuclear fuel core, etc.). That disposal may occur in an unauthorized manner, or be part of a comprehensive recover and reuse program. Unauthorized disposal may include dumping into the air, water, or ground, burning, mixing with other materials, or simply abandoning them where they reside.

## GENERAL HAZARDOUS MATERIAL INFORMATION

A chemical is an element, chemical compound, or mixture of elements or compounds, or both, including the final product in which it exists. Elements are the purest form of a chemical: gaseous oxygen (the molecule O) is an element. Compounds are elements that are joined chemically (e.g., water $H_2O$). Mixtures are two or more elements or compounds in a single vessel, but they are not bonded chemically. Ammonium nitrate and diesel, that together create the blasting agent called ANFO, are an example of a mixture.

Identification of hazardous materials is one of the most difficult tasks encountered by an inspector. Often very little information is available. The owner or employee of an occupancy containing hazardous materials may not be of much help.

Some hazardous materials are immediately dangerous to life and health (IDLH). This means that the concentration of airborne contaminants poses a threat of death, immediate or delayed permanent adverse health effects, or effects that could prevent escape from such an environment.

The model building and fire codes divide hazardous materials into two major categories: physical hazards and health hazards.

- A chemical (pure, mix, compound, or finished product) is a physical hazard if it will "cause or contribute to a fire or explosion."
- A chemical (pure, mix, compound, or finished product) is a health hazard if it has "statistically significant evidence of acute or chronic risks to exposed persons."

## Physical Hazards

The following groups create the "physical hazard" materials:[1]

1. **Explosives, blasting agents, and fireworks**. Chemical compounds, mixtures, or devices, the primary or common purpose of which is to function by explosion. The term includes, but is not limited to, dynamite, black powder, pellet powder, initiating explosives, detonators, safety fuses, squibs, detonating cord, igniter cord, igniters, and display fireworks, 1.3G (Class B, Special).

2. **Flammable and combustible liquids**.

   a. **Flammable liquids**: A liquid having a closed cup flashpoint below 100 °F (38 °C).

   b. **Combustible liquids**: A liquid having a closed cup flashpoint at or above 100 °F.

   The category of flammable or combustible liquids does not include compressed gases or cryogenic fluids.

3. **Flammable solids and gases**.

   c. **Flammable solid**: A solid, other than a blasting agent or explosive, that is capable of causing fire through friction, absorption, or moisture, spontaneous chemical change, or retained heat from manufacturing or processing, or which has an ignition temperature below 212 °F (100 °C) or which burns so vigorously and persistently when ignited as to create a serious hazard.

   d. **Flammable gas**: A material which is a gas at 68 °F (20 °C) or less at 14.7 pounds per square inch atmosphere (psia) of pressure; a material that has a boiling point of 68 °F or less at 14.7 psia that:

[1] These definitions are paraphrased. Always refer to the statutes, codes, standards, or other regulations for detailed definitions.

- Is ignitable at 14.7 psia when in a mixture of 13 percent or less by volume with air; or
- Has a flammable range at 14.7 psia with air of at least 12 percent, regardless of the lower limit.

4. **Organic peroxides**. An organic compound that contains the bivalent -O-O- structure and which may be considered to be a structural derivative of hydrogen peroxide where one or both of the hydrogen atoms have been replaced by an organic radical.

5. **Oxidizer**. A material that readily yields oxygen or other oxidizing gas, or that readily reacts to promote or initiate combustion of combustible materials. Examples of other oxidizing gases include bromine, chlorine, and fluorine.

6. **Unstable (reactive) materials**. A material, other than an explosive, that in the pure state or as commercially produced, vigorously will polymerize, decompose, condense, or become self-reactive and undergo other violent chemical changes, including explosion, when exposed to heat, friction, or shock, in the absence of an inhibitor, in the presence of contaminants, or in contact with incompatible materials.

7. **Pyrophoric materials**. A chemical with an autoignition temperature in air, at or below a temperature of 130 °F (54 °C).

8. **Water reactive chemicals**. A material that explodes; violently reacts; produces flammable, toxic, or other hazardous gases; or evolves enough heat to cause autoignition or ignition of combustibles upon exposure to water or moisture.

9. **Cryogenic fluids**. A fluid having a boiling point lower than -130 °F (-90 °C) at 14.7 psia.

## Health Hazards

The following groups create the "health hazard" materials[2]:

1. **Highly toxic and toxic materials**. A material which produces a lethal dose or lethal concentration in laboratory rats under controlled scientific parameters. Mixtures of these materials with ordinary materials, such as water, might not warrant classification as highly toxic. While this system is basically simple in application, any hazard evaluation that is required for the precise categorization of this type of material shall be performed by experienced, technically competent persons.

2. **Corrosive materials**. A chemical that causes visible destruction of, or irreversible alterations in, living tissue by chemical action at the point of contact. This term does not refer to action on inanimate surfaces.

[2] These definitions are paraphrased. Always refer to the statutes, codes, standards, or other regulations for detailed definitions.

When working with hazardous materials regulations in the model codes, it is important to remember that if an element, compound, mixture, or product has more than one hazard characteristic, all hazards must be addressed to satisfy the code. For example, if a product is a flammable, corrosive, and toxic liquid, all code requirements for each category must be met.

Where can you find definitive information to help you apply the model codes?

## REGULATORY AND INFORMATION SOURCES

The fire protection professional and code official have a variety of tools available to help with the recognition and control of hazardous materials and operations. Correct application of the locally adopted codes and standards begins with properly classifying the chemical or material in question.

It is important that the code official realize that no single source of information should be used for making decisions about hazardous materials. The complexities of hazardous materials, how they interact with one another and the environment, and the potential disastrous outcomes require that the fullest attention be given to their control.

### Superfund Amendments and Reauthorization Act of 1986

The Superfund Amendments and Reauthorization Act of 1986 (SARA) Title III (Pub. L. 99-499) includes a number of significant requirements for hazardous materials to enhance a community's and workers "right-to-know" the hazards of chemical materials to which they are or might be exposed.

#### Local Emergency Planning Committees

SARA Title III requires the creation of Local Emergency Planning Committees (LEPC) to include representatives from the following groups: State and local officials, law enforcement, civil defense, firefighting, environmental, hospital, media, first aid, health, transportation, and facility owners or operators subject to the emergency planning requirements.

As part of the planning process, the LEPC must evaluate available resources for developing, implementing, and exercising the plan. The plan must include the following:

- identification of facilities subject to planning provisions under Title III;
- identification of transportation routes for extremely hazardous substances;
- identification of risk-related facilities;
- methods and procedures for response;
- designated community and facility coordinators;
- procedures for public notification;
- methods for determining release occurrence and area affected;

- description of emergency equipment and facilities and those responsible; and
- evacuation plans and training programs.

The Environmental Protection Agency (EPA) was mandated by Congress to establish a list of chemicals to help focus local emergency planning activities. They list 406 Extremely Hazardous Substances (EHS) and established a Threshold Planning Quantity (TPQ) for each.

If any business or facility contains one of these EHSs in an amount equal to or greater than its respective TPQ, the facility owner or operator is required to notify the State Emergency Response Commission (SERC) and LEPC. These facilities must name a facility coordinator to work with the LEPC for specific inclusion of that facility in the local plan. Representative facilities covered under the planning provisions include not only major chemical manufacturing facilities, but also a wide variety of chemical users, such as farmers, dry cleaners, and other service-related businesses.

Exemptions under this provision apply only to marine vessels (ship/boat), Federal facilities, and transportation. Storage incidental to transportation is exempt, provided that the EHSs are still moving under active shipping papers and have not reached the final consignee.

Accidental releases of EHSs and other hazardous substances identified in the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA) must be reported to the LEPC and SERC. This requirement ensures immediate notification to local response personnel.

Title III contains a specific provision for the disclosure of chemical identity by facility owners or operators on chemicals for which facilities have made trade secret claims. This means the owner cannot shield the information on hazardous materials from the local fire and emergency services.

## Material Safety Data Sheets

One provision in the Act is the requirement for MSDS (Material Safety Data Sheets). These must be provided not only in the workplace for the worker's right-to-know under the Occupational Safety and Health Administration (OSHA), but also for emergency response agencies. These data sheets can provide a valuable source of information for the identification and control of all types of hazardous materials.

MSDSs contain:

- name, address, and telephone number of the chemical manufacturer;
- chemical and trade name;
- health and hazard data;
- hazardous ingredients;
- fire and explosive information;
- precautions and protection information;
- physical and reactivity data;

- environmental information; and
- information for emergency response agencies.

## HAZARDOUS MATERIALS IDENTIFICATION

### Initial Information

The initial information that should be obtained includes the name of the substance. This may be more difficult than one may think. The name may be a trade name only, which doesn't tell you anything about the hazard, or the name may be the chemical name only. It is very important to record the correct spelling of the chemical name. Some of the spellings will be very similar but there can be a big difference in the hazard or way that the material reacts.

In order to determine the classification, consult MSDS. An invaluable source of information for classification is the Code of Federal Regulations--Title 49 (49 CFR) *Transportation Parts 100-177*. Virtually every chemical is listed in paragraph 172.101. The hazard class is listed in the column beside the name. The DOT label is required on the container or package.

### Additional Information Sources

There are several other sources for obtaining this information:

- *Fire Protection Guide on Hazardous Materials* from the National Fire Protection Association (NFPA);
- *Flammable Hazardous Materials* (James H. Meidle);
- *Chemistry of Hazardous Materials* (Eugene Meyer);
- *Fire Protection Handbook*, latest edition (NFPA);
- *Guide to Fire Hazard Properties of Flammable Liquids, Gases, and Volatile Solids* (formerly NFPA 325);
- NFPA 497, *Recommended Practice for the Classification of Flammable Liquids, Gases, or Vapors and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas*;
- NFPA 499, *Recommended Practice for the Classification of Combustible Dusts and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas*;
- NFPA 35, *Standard for the Manufacture of Organic Coatings*;
- chemical dictionaries;
- colleges, universities, technical schools;
- third-party consultants or experts;
- Chemical Abstract Service (CAS);
- National Institute of Occupational Safety and Health (NIOSH) (www.niosh.gov);
- U.S. Department of Labor, Occupational Safety and Health Administration (OSHA) (www.osha.gov);
- EPA (www.epa.gov);

- National Institutes of Health (NIH);

  - Wireless Information System for Emergency Responders (WISER), and
  - Substance identification by list or physical characteristics;

- chemical manufacturers and distributors; and
- appendices and commentary from the model code groups.

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# Activity 6.1

## Classifying Hazardous Materials

### Purpose

To identify and classify hazardous materials for code enforcement purposes.

### Directions

1. You will be given a list of 11 chemicals or compounds.
2. For each chemical or compound, you are to identify
   a. Physical state.
   b. Hazard classification.
   c. Source(s) of information.
3. You must cite at least three different information sources for your findings.
4. Your list is due tomorrow morning.

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## Activity 6.1 (cont'd)

| Material | Physical State | Hazard Classification | Information Sources | | |
|---|---|---|---|---|---|
| | | | **Note: Any 3 reliable resources are accepted** | | |
| Gasoline | | | | | |
| Formic acid | | | | | |
| Silver oxide | | | | | |
| Chlorobenzene | | | | | |
| Diborane | | | | | |
| Pentabromophenol | | | | | |
| Anhydrous sodium dichromate | | | | | |
| Potassium borohydride | | | | | |
| Argon | | | | | |
| 2-methylpropane | | | | | |
| Perfluorooctane | | | | | |

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## HAZARDOUS MATERIAL CONTROL CONCEPTS

This course emphasizes hazardous material control concepts in the built environment. There are numerous other courses available for transportation regulations and emergencies; those topics will not be covered here.

There are four fundamental concepts employed to control hazardous materials and prevent them from becoming a response problem:

- awareness, education, and training;
- proper handling and storage;
- ignition control; and
- limiting quantities.

### Awareness, Education, and Training

Awareness, education, and training apply to everyone who may come into contact with hazardous materials at some point in the hazardous material "life cycle:" producers, employees, handlers, shippers, emergency response personnel, code officials, and the public.

We have discussed already some of the challenges pertaining to hazardous materials: making people aware of inherent dangers. This can be accomplished simply through published warnings or directives. Think about the "No Smoking--Stop Your Engine" signs at the local motor vehicle service station. Once they warned only about the dangers associated with heat sources, but now they include warnings about cellular telephones, inhaling gasoline vapors, or filling "unapproved" containers.

Awareness also can be addressed in the workplace where employees are required to have initial and continuing education on hazardous materials to protect themselves, their coworkers, and the facility and products.

Education involves providing users and consumers with fundamental knowledge about a product; its intrinsic hazards such as flammability, toxicity, or reactivity. Education occurs in both formal and informal settings.

Training involves reviewing lessons learned, safe operating practices, recovery and reclamation efforts, and practicing safe workplace controls. Generally, training is targeted at manipulative skills needed to prevent an accident such as properly bonding and grounding vessels before transferring products, using powered industrial trucks (forklifts) in a safe manner, and assuring portable fire extinguishing equipment is available and operational.

## Proper Handling and Storage

Federal regulations provide comprehensive rules for the vessels in which hazardous materials are kept. Whether it is DOT regulations for over-the-road trucks or the thickness of paper or polyethylene bags for dry products, these regulations address the variety of environments in which specific products may be found.

Problems occur, through, when products are removed from their original container, the container is damaged, or containers are stored improperly. The building and fire codes have specific requirements for how materials must be handled and stored based on their inherent risks. The code official's responsibility is making certain that these rules are followed.

Take, for example, the local "big box" garden supply store. You are likely to find thousands of pounds of dry chemical fertilizers, pesticides, or other products. You may find liquid products on shelves or racks or in containers on the floor. There may be products in pressurized aerosol containers. The model building and fire codes specify how those materials must be stored to prevent accidents or spills, and if a spill or accident occurs, what steps must be taken to mitigate the hazard.

Some hazardous materials are so dangerous alone or with one another that they must be stored or used in special buildings away from other occupancies. Dynamite manufacturing and storage, for example, must occur in what is called "detached" storage well away from exposures. The separation distances are based on the amount of hazardous materials. "Incompatible" chemicals that might interact spontaneously with others causing a fire, explosion, toxic fuming, or other hazard must be stored away from one another. (See Table 6-1 in the Appendix for a matrix of some incompatible chemicals.)

## Quantity Limitations

Limiting the amount of hazardous materials in an occupancy is the fourth control concept. Look around the room in which you are right now. If someone where to bring a thimbleful of acetone into the space, you would acknowledge that it is a hazard, but likely not be too concerned. However, if someone were to wheel a 55-gallon drum of acetone into the same room, few people would argue that a hazardous condition has been created.

By limiting the amount of hazardous materials in a space--based on hazard class and use of the space--the likelihood of a dangerous condition can be minimized.

## REGULATORY PROCEDURES

Effective hazardous material regulation (code enforcement) involves five factors:

1. Knowing the materials' identity and hazardous characteristics.

2. Identifying its physical state.

3. Identifying and controlling the environment where the hazardous materials are present.

4. Identifying and controlling the vessels in which the hazardous materials occur.

5. Knowing the amount of hazardous materials that will be in a given environment.

We already briefly have discussed the first factor: knowing the material and its characteristics.

## Physical State

There are three main states of matter: solid, liquid, and gas. (There actually are five: solid, liquid, gas, plasma, and Bose Einstein condensates, but the codes do not address the latter two.) The physical state in which a hazardous material occurs may influence the code requirements, particularly the amount of material that may be allowed within a space.

Not every material occurs in a discrete physical state or phase. For example, the gaseous physical state includes gases at atmospheric pressure, compressed gases, liquefied gases, and cryogenic gases. Other materials may migrate from phase to phase depending upon outside influences such as temperature or pressure.

The code enforcement official must be able to identify the product's physical state. This generally can be obtained from the MSDS.

## Environment

The "environment" in which the hazardous materials are found significantly affects the way building and fire codes are applied. The code official must have adequate information to establish the environment where the materials will occur.

"Environments," as defined in the codes, include

- Storage: where the material is kept in closed containers, tanks, cylinders, bags, or similar vessels. Generally, this is considered the "least hazardous" environment. Products in storage include such items as paint and coatings in wholesale or retail display, bagged dry products such as fertilizer or pesticide, underground or aboveground tank storage of bulk fuels, and compressed gases in bulk warehouses. Storage is considered the "least hazardous" environment because the products are contained within vessels that were designed to hold them, and there are no flammable or toxic constituents exposed to the atmosphere where than can create ignitable or dangerous mixtures or affect unprotected personnel.

- Use: where the material is "placed into action." Once a five-gallon container of paint thinner or similar product has been opened, it is considered to be in "use." Even if it remains in its original container, and is put back on a shelf or cabinet when not being made use of, it is considered in "use."

- Dispensing: where the product is poured, pumped, or somehow transferred from one vessel to another where vapors, dusts, fumes, mists, or gases are liberated to the atmosphere. Generally, this is considered the "most hazardous" environment because the product is exposed to air and may create ignitable or dangerous mixtures or affect unprotected personnel.

- Handling: where the product is transported by any means to a point of storage or use. This may be through a network of pipes and valves, a powered industrial truck, or simply a hand-operated utility cart designed to transport small vessels. "Offsite" transportation usually is regulated by the DOT, not the fire codes.

## Vessels

While the term "vessel" may evoke romantic images of a ship sailing off into the sunset, there is an important reason the term is used when discussing hazardous materials. In the building and fire codes, the terms used to describe various items in which they are stored have specific definitions and must be used with precision to apply the codes properly. A "container," for example, means a vessel having a capacity up to 60 gallons. A vessel larger than 60 gallons is a "tank" that might be "portable" or "stationary." The term "vessel" is used generically to describe any means of storage or piping. (Although the petroleum industry recognizes a "barrel" of oil as 42 gallons, there is no similar term in the codes.)

A "portable" tank generally has a liquid capacity of more than 60 and up to 660 gallons. Portable tanks usually are mounted on skids or some other means that allows them to be moved with appropriate handling apparatus. A tank larger than 660 gallons is considered stationary by definition, and is regulated by the aboveground and underground tank rules for stationary tanks.

The term "cylinder" generally applies to compressed gases that are pressurized or even liquefied. Liquefied petroleum gases (LPG) are stored either in small, upright cylinders, or large horizontal tanks.

When discussing cryogenics, the terms "carboy" and "dewar" often appear. A carboy is a metal vessel with a narrow neck much like a big jug used to make wine. A dewar is a metallic container used to store cryogenics like liquid nitrogen or oxygen.

## Quantity Limits

Once the material, its physical state, its environment, and container have been determined, the final code consideration is the amount of material that may occur in a space such as a room, building, or even outdoors. The building and fire codes establish what are called "maximum allowable quantities" that may be stored, used, dispensed, or handled depending upon the circumstances. In general, the maximum allowable quantities for products in storage are greater than those for in use or dispensing, because products in storage are considered less hazardous and therefore more can be allowed in a space.

The codes provide tables of maximum allowable quantities depending upon the physical state and environment. The tables are based on what is called the "control area" concept. Control areas are spaces within a building or outside where the quantities of hazardous materials not exceeding the maximum allowable quantities per control area are stored, dispensed, used, or handled. One building could be an entire control area, an outside storage area could be a control area, or a building might have multiple indoor and outdoor control areas depending upon its operation.

**Example 1**--The local "big box" home improvement store consists of an open retail sales area and a marshaling area in the back that is not separated by any fire-resistive construction. This arrangement is a single indoor control area.

**Example 2**--The local hardware store in the strip mall has a main retail sales area, and a small store room that is separated from the retail sales area by 1-hour fire-resistive construction. This arrangement creates two control areas. Indoor control areas generally are separated from the rest of the occupancy by 1-hour fire barriers.

**Example 3**--The compressed refilling merchant has an outdoor space where he stores flammable and oxidizing gases, cryogens, and liquid corrosives. This is an example of an outdoor control area.

**Example 4**--The university science building has an outdoor marshaling yard where chemicals are delivered and stored awaiting distribution; and four labs on different floors of the building that are separated from the rest of the occupancy by 1-hour fire-resistive construction. This is an example of one outdoor control areas and four indoor control areas.

## Exceeding the Maximum Allowable Quantities

If the maximum allowable quantities are exceeded, the operation becomes a hazardous occupancy. Once a space goes from one occupancy type to a hazardous occupancy, the building and fire code requirements become especially complicated and expensive. For example, a medical office (business occupancy) may need to have a small amount of hazardous materials for its operation. The business is allowed up to the maximum allowable quantity and remains a business occupancy. Once the maximum allowable quantity is exceeded, the occupancy group changes from business to hazardous, requiring substantially more life safety and fire protection features. Table 6-7 is an example of maximum allowable quantities based on product category. It is **not** a complete maximum Allowable Quantity table, and is used only for illustrative purposes.

**WARNING**

1. **Always** refer to the legally adopted building or fire code for complete details applicable to your jurisdiction.

2. **Always** read and follow the footnotes to the tables.

3. **Always** read the exceptions to the tables and text.

# Table 6-1
## Sample Maximum Allowable Quantity per Control Area Tables (Extract)

### Hazardous Materials Creating a Physical Hazard

| MATERIAL | CLASS | GROUP WHEN MAQ IS EXCEEDED | STORAGE | | | USE-CLOSED SYSTEM | | | USE-OPEN SYSTEM | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | SOLID Pounds (cubic feet) | LIQUID Gallons (pounds) | GAS Cubic feet at NTP | SOLID Pounds (cubic feet) | LIQUID Gallons (pounds) | GAS Cubic feet at NTP | SOLID Pounds (cubic feet) | LIQUID Gallons (pounds) |
| Combustible Liquid | II<br>IIIA<br>IIIB | H-2 of H-3<br>H-2 or H-3<br>Not Applicable | Not Applicable | 120<br>330<br>13,200 | Not Applicable | Not Applicable | 120<br>330<br>13,200 | Not Applicable | Not Applicable | 30<br>80<br>3,300 |
| Combustible Fibers | Loose<br>Baled | H-3 | (100)<br>(1,000) | Not Applicable | Not Applicable | (100)<br>(1,000) | Not Applicable | Not Applicable | (20)<br>(200) | Not Applicable |
| Flammable Gas | Flammable<br><br>Liquefied | H-2 | Not Applicable | Not Applicable<br>30 | 1,000<br>Not Applicable | Not Applicable | Not Applicable | 1,000<br>Not Applicable | Not Applicable | Not Applicable |
| Flammable Liquid | IA<br><br>IB and IC | H-2<br>or<br>H-3 | Not Applicable | 30<br><br>120 | Not Applicable | Not Applicable | 30<br><br>120 | Not Applicable | Not Applicable | 10<br><br>30 |
| Oxidizer | 4<br>3<br>2<br>1 | H-1<br>H-1 or H-2<br>H-3<br>Not Applicable | 1<br>10<br>250<br>4,000 | (1)<br>(10)<br>(250)<br>(4,000) | Not Applicable | 0.25<br>2<br>250<br>4,000 | (.25)<br>(2)<br>(250)<br>(4,000) | Not Applicable | 0.25<br>2<br>50<br>1,000 | (0.25)<br>(2)<br>(50)<br>(1,000) |

### Hazardous Materials Creating a Health Hazard

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Corrosive | | H-4 | 5,000 | 500 | 810 | 5,000 | 500 | 810 | 1,000 | 100 |
| Toxic | | H-4 | 500 | (500) | 810 | 500 | (500) | 810 | 125 | (125) |

**Note:** These are not the entire Maximum Allowable Quantity Tables from the building or fire codes, and this extract is included only for illustrative purposes. Always Refer to the legally-adopted building or fire codes for accurate information. Always read the footnotes and exceptions, if any.

In the table on the previous page, note that some of the values have parentheses around them. Look at the column headers and you will see that some are in two units, with the second unit in parentheses. The values in the parentheses correspond to the units in parentheses. For example, in the column for "combustible fibers" in solid storage, the value for loose fibers is (100) and the value for baled fibers is (1,000). These values represent cubic feet rather than pounds.

You also will note that for some materials, the values for pounds appear to be the same as the values for gallons. Look at the entry for "Class 2 oxidizers." In the "solids" category, the maximum allowable quantity is 250 pounds. In the "liquids" category, the maximum allowable quantity also is (250). If you look at the header of the table, you'll see that the parentheses around the units means the value also should be read in pounds. Confusing? This illustrates the importance of reading the footnotes. This particular table has a footnote that says "For gallons of liquid, divide the amount in pounds by 10." The maximum allowable quantity for liquid gallons then is 25. For oxidizers, it doesn't matter if the value is listed in pounds or gallons; it is the mass of the material that contributes to the chemical oxidation/reduction reaction. One hundred pounds of an oxidizer equals 10 gallons of an equivalent amount of energy.

Another important point is that an occupancy may have up to the maximum allowable quantity of **all** the different material categories, and not be classified as a hazardous occupancy. For example, a nonsprinklered metal fabricating shop could have 10 gallons of Class IA liquids in open use, 120 gallons of Class IB liquids in storage, 13,200 gallons of Class IIIB liquids in storage, 1,000 $ft.^3$ of flammable gases in storage, another 1,000 $ft.^3$ of flammable gases in closed system use, etc., and would remain a low-hazard factory or industrial occupancy.

## Avoiding the "Hazardous Occupancy"

There are several options a property owner or tenant can chose to increase the total amount of maximum allowable quantities within a control area to avoid becoming a hazardous occupancy.

The first is the use of approved flammable liquid or hazardous materials storage cabinets. Generally, the codes allow the owner to double the amount of product if is stored in an approved cabinet. The metal fabricating shop in the previous example could have 240 gallons of Class IB liquids in storage if 120 gallons of the total were stored in cabinets.

Second, the installation of an automatic sprinkler system often allows a doubling of the maximum allowable quantity. If the metal fabricating shop were sprinklered, the occupant could have 240 gallons of Class IB liquids in storage "in the open" without cabinets.

For some materials, the combination of cabinets and sprinklers allows redoubling the values. The sprinklered metal fabricating shop could have could have 240 gallons of Class IB liquids in storage "in the open," and another 240 gallons in cabinets for a total of 480 gallons of IB liquids.

Adding more control areas might be another solution to keep increasing the amount of product in storage, use, dispensing, or handling, as long as the number and location of control areas does not exceed the amount permitted by the codes. Furthermore, as additional control areas are

created--especially on floors above grade or in basements--the amount of hazardous materials allowed in each is reduced by a specific percentage.

If all of the options are exhausted, the occupancy becomes a hazardous occupancy if additional hazardous materials are introduced. In the case of the metal fabricating shop, the employed sprinklers and cabinets in one control area to increase its maximum allowable quantity, any amount of Class IB liquid above 480 gallons would require an occupancy change to a hazardous occupancy.

## BASIC CONTROL MEASURES

Generally the principles of preventing the fire, explosion, toxicity, and environmental hazards associated with hazardous materials include a comprehensive control strategy with many supporting actions.

### Controlling Ignition Sources

Excluding ignition sources from areas where products are stored, used, dispensed, or handled may be a significant challenge because there are so many and they are so varied. Some ignition sources may be obvious, such as unregulated smoking, open flames, heating appliances, or electrical faults (sparks, arcs, and static). Other ignition sources may be just as dangerous but less obvious: friction, compression, materials handling equipment (conveyors, powered industrial trucks), or even sunlight.

### Air or Water Exclusion

For some materials, the exclusion of air (oxygen) or creating inert environments may be the preferred control method. Some alkali metals (potassium, cesium), finely divided metal dusts (nickel, zinc, titanium), and hydrides (barium hydrides, diborane, diisobutyl aluminum hydride) are classified as "pyrophoric" materials because they react spontaneously in air. By creating storage environments that exclude oxygen (often by replacing the atmospheric air with inert nitrogen) these products may be protected from igniting.

Water reactive chemicals such as alkali metals (sodium metal, lithium metal), anhydrides (acetic anhydrides), carbides (calcium carbide), halides (acetyl chloride, titanium chloride, stannous chloride), and some peroxides must be kept where they cannot come into contact with water or humid air.

### Storage and Handling Practices

Safe storage and handling practices are essential when dealing with hazardous materials. The MSDS often will describe in detail the precautions that should be taken such as protection from

shock, padding, storing liquids in closed containers or systems, using only packaging materials that are appropriate for the chemical, keeping pile sizes small so personnel or materials handling equipment can get to it without overreaching, or storing materials on compatible shelves, decks, dunnage, or racks.

Handling or product transfer may require special automatic control valves, self-closing and sealing dispensers, emergency vents for containers or tanks, spill control, drainage and diking (described below) or special materials such as stainless steel pipe or tube, glass drainage tubes, or plastic materials.

In all cases, storage, handling, and product transfer should match the recommendations of the product manufacturer and the fire or building codes.

## Ventilation

Ventilation may be provided to prevent vapor accumulations of vapor within the flammable range of specific products, or may be used to evacuate or control toxic vapors during an emergency. Ventilation may be provided by providing natural means or mechanical exhaust ventilation systems, depending upon the hazardous materials and their characteristics. Some ventilation systems may be required to run continuously while others may be designed for emergency operation only, connected to a fire protection system or controlled manually by emergency forces.

When ventilation is used to dilute vapor concentrations below the flammable range of a product, the codes generally require that the air exchange rate be sufficient to keep the vapor:air ratio below 25 percent of the product's lower explosive limit (LEL) to provide an extra safety margin. To compute the ventilation system capacity, the system designer must know the product's LEL, the amount of product that will be in the space, and the space's volume so that the ventilation system can be sized appropriately.

## Separation by Segregation or Isolation

An important control principle is to store "incompatible" hazardous materials away from one another so they don't mix and create a greater hazard. Again, reference to Table 6-1 in the Appendix to this unit provides list of common incompatible chemicals. This list is a sample, and does not include all the possible chemicals or combinations. Chemical incompatibility in pure, mixture, and compound states should be determined only by a qualified chemist.

When chemicals must be separated from one another, it can be done by keeping them apart (in small quantities) or, when the codes require, by "segregation" or "isolation." Chemicals that must be segregated must have at least 20 feet of clearance between them. When the codes allow hazardous materials to be isolated from one another, they may be in the same room or even on the same shelf as long as there is a noncombustible barrier between them that extends at least 18 inches beyond the chemicals on all sides.

## Exposure Protection

Some hazardous materials that may detonate or deflagrate may be stored or used in facilities outfitted with explosion venting or explosion suppression systems. The design and construction of explosion venting is specified in the building codes, and generally consists of lightweight construction that it "lightly attached" to the rest of the building so the explosive shock pressure wave will cause it to fail while the rest of the building remains intact. Generally, these designs are arranged to vent the pressure away from occupied spaces into empty yards or even fire lanes, creating a potential hazard for first responders.

Explosion suppression systems employ ultrafast acting detection devices that trigger the release of water or chemical fire protection systems to control the shock wave before it travels very far from the ignition source. Explosion suppression systems often are found in product-conveying duct systems (conveyors, flammable gas ventilation or transfer, fine particle dust control, etc.) where an explosion could travel quickly through the duct system to the rest of the building.

## Chemical and Fire Detection and Protection Systems

Should the product escape from its vessel, a variety of means exist to detect and control the problem. Automatic detection devices can be manufactured to detect one or more specific hazardous chemicals. Industrial facilities commonly install these devices to notify employees and emergency responders of problems, and initiate automatic control mechanisms such as production shut down or fire protection systems. Fire and smoke detection systems also can be used to detect potentially catastrophic conditions once the hazardous materials ignite.

There is a variety of fire protection systems that can be used to control chemical hazards. Automatic sprinklers and deluge systems, open nozzle water spray, carbon dioxide, foam:water, high-pressure water mist, clean agents, or inerting agents such as nitrogen can control hazardous incidents. They key to successful control is to assure that the fire suppression agent (i.e., water, foam of $CO_2$) is matched properly to the product or products being protected, the system design is adequate to handle the scale of the emergency, and the system has been inspected, tested, and maintained properly to operate in an emergency.

## Fire-Resistive Construction

Fire-rated separation walls, floors, and ceilings, with rated opening protectives, provide another layer of protection. Separation assemblies that are rated from 1 to 4 hours will aid in the confinement of hazardous events until other control mechanisms--including manual fire suppression--are brought into play.

## Containment

The vessel in which a hazardous material is located is called its "primary container." A 1-gallon paint can, a 50-pound fertilizer bag, a liquefied oxygen dewar, a LPG cylinder, a toxic gas piping system, and a million-gallon fuel oil storage tank all are "primary containers." Generally, as long as the hazardous material remains inside its primary container, its hazards can be controlled.

For some solid or liquid products though, unintentional leaks or spills can create serious problems, so an additional layer of control security may be required. Think about the bulk fuel storage facility in your jurisdiction. Most, if not all, of the storage tanks probably are surrounded by low earthen or masonry berms known as "dikes." These dikes create "secondary containment" so if one tank loses its contents, it will not flow unimpeded to other areas, such as around other tanks or important buildings on the site. Secondary containment generally must be sized to accommodate the volume of the largest vessel it surrounds, plus a specific amount of rainwater (if located outdoors) and/or fire protection water (sprinkler discharge), if located indoors. Some secondary containment facilities may have overflows or drains that can carry the contents away from the source to another location where the chemicals can be better controlled.

Other forms of secondary containment are the:

- Popular double-walled tank that has an inner vessel that holds the product, plus an outer container that will hold the product if the primary vessel leaks.
- Protected tanks that are encased in concrete or some other fire-resistive material. These commonly are seen at motor vehicle fueling stations where underground tanks may be undesirable due to the potential for environmental damage.
- Underground or aboveground vaults that usually are made of concrete and the primary tanks are set inside.
- Concrete special enclosures that can be built around aboveground tanks.
- Indoor or outdoor liquid-tight sloped or recessed floors.
- Indoor or outdoor liquid-tight raised or recessed sills or dikes.
- Sumps and collection systems.
- Drainage systems that can carry products to an approved location.
- Any other method that has been engineered properly and is approved by the code official.
- Containment pallet.

A "containment pallet" is a materials handling method that has a liquid-tight sump capable of visual inspection and able to hold at least 66 gallons of liquid. (Remember, a "container" is a

primary vessel up to 60 gallons capacity; the additional 6 gallons is a 10-percent safety margin included to accommodate rainwater or other materials that might accumulate in the sump.) The exposed surfaces of the containment pallet must be compatible with the hazardous materials being stored on it.

A third method of containment is "spill control." Spill control differs from secondary containment in that it is designed specifically to control unintentional liquid spills. The capacity of the selected spill control method has to equal only the volume of the largest vessel in the space.

Spill control can be accomplished by:

- indoor or outdoor liquid-tight sloped or recessed floors;
- indoor or outdoor liquid-tight raised or recessed sills or dike;
- sumps and collection systems;
- any other method that has been engineered properly and is approved by the code official; and
- containment pallets.

## Warning Signs and Markings

Whenever hazardous materials occur in significant quantity, adequate warning signs should be provided to protect employees, the public, and first responders. Warning signs may be as simple as "No Smoking or Open Flame" or as detailed as "Danger! Never Fight Explosives Fires. Explosives are Stored on This Site. Call _____." The building and fire codes provide guidance as to when and where these types of warning signs are provided.

Many firefighters are familiar with the United Nations/Department of Transportation (UN/DOT) four-digit hazardous materials identification system. The UN/DOT labeling system is used for materials involved in interstate shipping and is not applicable to fixed facilities.

NFPA 704, *Standard System for the Identification of the Hazards of Materials for Emergency Response*, establishes a marking system used where materials are stored, handled, or used. It applies only to stationary facilities, not transportation. The system can be used for buildings, tanks, and piping that store, use, dispense, or handle hazardous materials.

This is the best marking system of hazardous materials currently available, both from a prevention point of view and a firefighting point of view. It is a complete system that identifies the characteristics that are most important for safety. These include

- fire hazard (flammability) [red];
- health hazard (toxic, irritant) [blue]; and
- chemical reaction hazard [yellow].

In addition, the white portion of the sign can be used to identify such other special hazards as radiation and water reactivity.

Use of a combination of colors and numbers allows someone who is familiar with the system to identify the relative hazard of the materials involved easily in all important safety categories. The numbers used indicate the relative hazard within each main category beginning with zero (0) which indicates no special hazard, through four (4) which indicates a severe hazard.

**Figure 6-1**
**LPG Storing Facility**

This facility storing LPG has provided a "No Smoking" sign and elected to include the UN/DOT placard.

## Gas Cylinder Marking

Compressed gases are transported and stored in a variety of pressure vessels. They often are color-coded by the gas manufacturer to identify the cylinders' contents. For example, anyone who has worked in emergency medical services (EMS) is aware of the familiar green medical oxygen cylinder. However, there is no mandatory color-coding system for compressed gas cylinders, so relying on color alone to predict what might be inside may be extremely dangerous. The U.S. DOT requires cylinders to be identified with a label near the neck to show what is contained in the cylinder.

The Compressed Gas Association (CGA) has adopted a system for color coding compressed gas cylinders: *CGA C-7 Guide to the Preparation of Precautionary Labeling and Marking of Compressed Gas Cylinders*. **This system is not used at all times and should be considered unreliable**. CGA recommended colors are as follows:

- green--oxygen;
- blue--nitrous oxide;
- brown--helium;
- red--ethylene;
- orange--cyclopropane; and
- gray--carbon dioxide.

Color combinations are used for gas mixtures of certain percentages, for example, medical nitrous oxide often is stored in a green cylinder with a blue top.

### Education and Training

Introducing human interaction with hazardous materials increases the risk of fire, explosion, toxic release, or environmental damage. A key strategy to reduce risk is to assure that persons who handle hazardous materials are aware of and educated properly about the hazards, and trained to prevent and handle accidents.

Education and training includes

- knowing the hazardous properties of the chemicals to be stored or handled;
- informing people in the area where the chemical is handled as to its hazards;
- describing facility safety plans, policies, and procedures;
- informing employees, and sometimes testing them on Federal, State, and local hazardous materials regulations;
- explaining the need to use good housekeeping techniques;
- learning precautionary handling, storage, dispensing, and use procedures;
- describing how to clean up spilled material immediately in accordance with safe practices;
- explaining danger signals (including physiological as well as technological), describing and practicing proper steps to take in case of an emergency; and
- explaining how to report and document education, training, preventative actions, and emergencies.

## COMMON CONTROL ISSUES

Regardless of whether the material involved is a flammable or combustible liquid, chemical, gas, or explosive, electrical systems, static electricity, and materials handling equipment all represent potential ignition sources. Proper design, use, and maintenance of these systems is a major control mechanism for these hazards.

### Hazardous or Classified Locations

Where fire or explosion hazards may exist due to flammable gases or vapors, flammable liquids, combustible dust, or ignitable fibers or flyings (lightweight combustible materials), electrical equipment must be "classified" based on the hazard. These rules are established within the adopted electrical code.

Locations are classified depending on the properties of the flammable vapors, liquids, gases, or combustible dusts or fibers that may be present, and the likelihood that a flammable or combustible concentration or quantity is present. Once the classification is established, open, closed, or explosion-proof electrical wiring and equipment must be installed. Each room, section, or area is considered individually in determining its classifications.

When pyrophoric materials are the only materials stored, used, or handled, these locations are not classified because if the material escapes from its container it ignites spontaneously in air, regardless of potential ignition sources.

## CLASSIFICATION SYSTEM

The classification system first establishes the "class" involved:

- **Class I locations** are where flammable gases or vapors are or may be present in the air in sufficient quantities to produce explosive or ignitable mixtures.

- **Class II locations** are hazardous because of the presence of combustible dust.

- **Class III locations** are hazardous because of the presence of easily-ignitable fibers or flyings, but where such fibers or flyings are not likely to be in suspension in the air in quantities sufficient to produce ignitable mixtures.

### Class I Gases and Vapors

The gases and vapors of Class I locations are broken into four groups: A, B, C, and D. These materials are grouped according to the ignition temperature of the substance, its explosion pressure, and other flammable characteristics.

The only substance in Group A is acetylene. Acetylene makes up only a very small percentage of hazardous locations. Consequently, little equipment is available for this type of location. Acetylene is a gas with extremely high explosion pressures.

Group B is another relatively small segment of classified areas. This group includes hydrogen and other materials with similar characteristics. If specific restrictions are met to satisfy the electrical code, some of these Group B locations--other than hydrogen--can be satisfied with Group C and Group D equipment.

Group C and Group D are by far the most usual Class I groups. They comprise the greatest percentage of all Class I hazardous locations. Found in Group D are many of the most common flammable substances such as butane, gasoline, natural gas, and propane.

## Class II Dusts

Groups E, F, and G are found in Class II dust locations. These groups are classified according to the **ignition temperature** and the **conductivity** of the hazardous substance. Conductivity is an important consideration in Class II locations, especially with metal dusts.

Group E dusts included combustible metals dusts (including aluminum, magnesium, and their commercial alloys), or other combustible dusts whose particle size, abrasiveness, and conductivity present similar hazards in the use of electrical equipment.

Group F atmospheres contain materials such as carbon black, charcoal dust, coal, and coke dust.

Group G includes grain dusts, flour, starch, cocoa, and similar types of materials.

See Table 6-8 on the following page for a summary of the hazardous area classification system.

**Table 6-2**
**Summary of Class I, II, III Hazardous Locations**

| Classes | Groups | Divisions | |
|---|---|---|---|
| | | 1 | 2 |
| I<br><br>Gases, vapors, and liquids | A: Acetylene<br><br>B: Hydrogen, etc.<br><br>C: Ether, etc.<br><br>D: Hydrocarbons, fuels, solvents, etc. | Normally explosive and hazardous | Not normally present in an explosive concentration (but may accidentally exist) |
| II<br><br>Dusts | E: Metal dusts (conductive and explosive)<br><br>F: Carbon dusts (some are conductive and all are explosive)<br><br>G: Flour, starch, grain, combustible plastic, or chemical dust (explosive) | Ignitable quantities of dust normally are, or may be, in suspension, or conductive dust may be present | Dust not normally suspended in an ignitable concentration (but may accidentally exist); dust layers are present |
| III<br><br>Fibers and flyings | Textiles, wood-working, etc., (easily ignitable, but not likely to be explosive) | Handled or used in manufacturing | Stored or handled in storage (exclusive of manufacturing) |

* Note: Electrically conductive dusts are dusts with a resistivity less than $10^5$ ohm-centimeter.

## Assessing Whether Class I or II Areas Exist

The code official may be called upon--and is authorized--to evaluate the potential risks that may result in classifying one or more spaces as "hazardous locations" in accordance with the electrical codes. The code official also may require a third-party evaluation to make recommendations based on the following procedures:

### Class I Hazardous Areas

Procedure for classification of Class I areas:

- Have there been instances of leaks?

- Do leaks occur frequently?
- Do leaks occur during normal or abnormal operation?
- Is the equipment in good condition, questionable condition, or in need of repair?
- Do maintenance practices result in the formation of ignitable mixtures?
- Does routine flushing of process lines, changing of filters, opening or equipment, and so forth result in the formation of ignitable mixtures?

### Procedure for Classification for Class II Areas

- Is a dust likely to be in suspension in air continuously, periodically, or intermittently under normal conditions in quantities to produce an ignitable mixture?
- Are there dust layers or accumulations on surfaces deeper than 1/8 inch?
- Are there dust layers or accumulations on surfaces that make the colors of the floor or equipment discernible?
- What is the 24-hour dust accumulation?
- Is the equipment in poor condition, questionable condition, or in need of repair?
- Do maintenance practices result in the formation of ignitable mixtures?
- What equipment is used for dust collection?

In determining the proper classification of an area, the quantity of combustible dust that may be present and the adequacy of dust removal systems are factors that merit consideration in determining the classification and may result in an unclassified area.

## Static Electricity Control Techniques

Precautions against sparks from static electricity are needed in locations where flammable vapors, gases, or dusts are present, or where there are easily-ignited materials.

Flowing gases, liquids, or granular solids will generate static electricity. An electrical charge can be built up. If a discharge of electrical energy occurs, a spark is caused and ignition of surrounding combustibles (gases, flammable liquid vapor, dust, etc.) can occur.

Static electricity means "the electrification of materials through physical contact and separation." The development of electrical charge may not in itself be a potential fire and explosion hazard unless the discharge of electricity occurs.

In order for static electricity to be a source of ignition, four conditions must be present:

1. An effective means of static generation.

2. A means of accumulating the separate charges and maintaining a difference of potential.

3. A spark discharge of adequate energy.

4. The spark must occur in an ignitable mixture.

Static electricity may appear as the result of motions that involve changes in relative positions of contacting surfaces, usually of dissimilar substances whether liquid or solid. One of these, or both, must be a **poor** conductor of electricity.

Examples of this type of motion which you will find in industry:

- flow of fluid through pipes and the accumulation of a charge on the surface of a nonconducting liquid;
- breaking up into drops of a stream of liquid and the resultant impact of such drops onto a solid or liquid surface;
- steam, air, or gas flowing from any opening in a pipe or hose when the steam is wet or the air or gas stream contains particulate matter;
- pulverized materials passing through chutes or pneumatic conveyors;
- nonconductive power or conveyor belts in motion; and
- moving vehicles.

You can see that you need to suspect static electricity generation in any process involving transfer of liquids, gases, and particulate matter as well as conveyor belts.

The best fire prevention is elimination of ignitable mixtures in areas where sparks of static electricity can occur. Methods for bringing the situation under control include

- humidification;
- bonding, grounding; and
- ionization.

## Humidification

Relative humidity in the atmosphere should be high. Static electricity is less prevalent in humid air. The static charge will dissipate. Humidity should be maintained up to approximately 75-percent relative humidity if possible and practical.

### Bonding and Grounding

These are the most common methods of prevention, especially with flammable liquids.

Bonding is done to minimize differences in electrical potential between metallic objects. There is practically no differential between two metal objects connected by a bond wire. The current carried by the wire is usually small.

When gasoline, for example, is transferred from a drum to a can, the drum and can should be bonded together before transfer by a tube which is conductive and firmly in contact at both ends, or a bonding wire should be attached securely to both containers before transfer. A bonding wire is necessary except where containers are inherently bonded together.

Grounding refers to connections made to minimize differences in electrical potential between objects and the ground. Ground connections must be designed properly and of proper capacity. They must be tested frequently to detect impairment by corrosion, loose connection, or injury.

In general, grounding and bonding connections should be of substantial construction so that they are not broken easily, and installed so you can tell that they are in place and intact.

Water pipes are usually suitable grounds. Any ground suitable for power circuits or lightning protection is adequate for static electricity.

### Ionization

Increasing the conductivity of the air so that charges will be conducted away. As an example: a flame ionizes surrounding air.

Alternating electrical fields are used when dealing with electrified sheet material. (Sheet is passed through the field.) This is called electrical neutralizer.

Ionization is a specialized technique that must be designed properly.

## Materials Handling Equipment--Powered Industrial Trucks

Powered industrial trucks include fork trucks, platform lift trucks, motorized hand trucks, and other specialized industrial trucks powered by electric motors or internal combustion engines. Used improperly, they can be an ignition source or added fuel to a fire.

## Classification of Types

Powered industrial trucks are classified based upon the level of protection against fire hazards, and in the case of electrical units--shock hazard.

Units with the minimum safeguards are inherent fire hazards and are the following types:

- CN--compressed natural gas-powered units;
- D--diesel-powered units;
- E--electrical-powered units;
- G--gasoline-powered units;
- LP--LP-powered units;
- G/CN--operates on either gasoline or compressed natural gas; and
- G/LP--operates on either gasoline or LP.

Units with additional safeguards are the following types. These units have the minimum safeguards plus the additional protection specified in each type:

- CNS--compressed natural gas with additional safeguards to the exhaust, fuel, and electric systems;
- DS--diesel-powered units with additional safeguards to the exhaust, fuel, and electric systems;
- DX--diesel-powered units for use in atmospheres that contain specifically-named flammable vapors, dusts, and, under certain conditions, fibers;
- DY--diesel-powered unit in which the electrical equipment is enclosed completely and is equipped with temperature limiting features;
- EE--electrical-powered unit that has all electric motors and other electrical equipment completely enclosed;
- ES--electrical-powered unit with additional safeguards to prevent the emission of hazardous sparks and to limit surface temperature;
- EX--electrical-powered unit for use in atmospheres that contain specifically named flammable vapors, dusts, and, under certain conditions, fibers;
- GS--gasoline-powered unit with additional safeguard to the exhaust, fuel, and electrical systems;
- GS/CNS--gasoline/compressed natural gas powered unit that has additional safeguards for exhaust, fuel, and electrical systems;
- GS/LPS--gasoline/LP powered unit that has additional safeguards to the exhaust, fuel, and electric systems; and
- LPS--LP powered unit with additional safeguards to the exhaust, fuel, and electric systems.

## Powered Industrial Trucks and Classified Locations

NFPA 505, *Fire Safety Standard for Powered Industrial Trucks Including Type Designations, Areas of Use, Conversations, Maintenance, and Operations* establishes where each type of powered industrial truck may be used, based on the hazardous area classification of the electrical code.

The code official must verify that the properly-classified powered industrial truck is used in the hazardous environment.

NFPA 505 includes a matrix that designates where certain classes of powered industrial trucks may be used or are prohibited. Table 6-9 on the following page is an example of the matrix. It is **not** the complete NFPA 505 table, and is used only for illustrative purposes.

## Table 6-3
## Matrix of Powered Industrial Truck Use Based on Hazardous Locations (Extract)

| | CNG | | Diesel | | | | Electric | | | | Gasoline | | LP Gas | | Dual Fuel | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Locations** | **CN** | **CNS** | **D** | **DS** | **DY** | **DX** | **E** | **ES** | **EE** | **EX** | **G** | **GS** | **LP** | **LPS** | **G/CN** | **GS/CNS** | **G/LP** | **GS/LPS** |
| **Class I, Division 1** | | | | | | | | | | | | | | | | | | |
| Group A | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| Group D | NA | NA | NA | NA | A | NA | NA | NA | NA | A | NA | NA | NA | NA | NA | NA | NA | NA |
| **Class I, Division 2** | | | | | | | | | | | | | | | | | | |
| Group A | NA | NA | NA | NA | K | K | NA | NA | K | K | NA | NA | NA | NA | NA | NA | NA | NA |
| Group B | NA | K | NA | K | K | K | NA | K | K | K | NA | NA | NA | K | NA | K | NA | K |
| Group C | NA | K | NA | K | K | K | NA | K | K | K | NA | K | NA | K | NA | K | NA | K |
| Group D | NA | J | NA | J | A | A | NA | J | A | A | NA | J | NA | J | NA | J | NA | J |

A = Type truck authorized for location described
J = Type truck authorized for location described with approval of the authority having jurisdiction
K = Type truck authorized to be determined by the authority having jurisdiction
NA = Type truck not authorized in location described

©*Fire Safety Standard for Powered Industrial Trucks Including Type Designations, Areas of Use, Conversions, Maintenance, and Operations*, NFPA 2006.

**Note:** This is **not** the entire matrix from the NFPA 505, and this extract is included only for illustrative purposes. Always refer to the legally-adopted building or fire codes for accurate information. Always read the footnotes and exceptions, if any.

# Activity 6.2

## Identifying Hazardous Material Control Features

### Purpose

To identify common hazardous material control features.

### Directions

1. You will be shown 20 photographs of common hazardous materials and related equipment or design features intended to control them.

2. Identify the means of hazardous material control that are visible in the photograph.

3. Be prepared to share your answers with the class.

### Photograph

1. _____

   _____

2. _____

   _____

3. _____

   _____

4. _____

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19. _____

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20. _____

_____

## SUMMARY

Today, what we recognize as hazardous materials are almost as common as the air we breathe. It is almost impossible to work, rest, or play without coming into contact with one or more hazardous materials in the course of our day.

For the building or fire code official to succeed in the recognition and control of hazardous materials, it is essential that one gains more than just basic information and knowledge about the products.

We must learn to identify hazardous materials with accurate information, overcome public complacency, and explore and find practical solutions to controlling hazardous materials to protect the public, workers, and first responders.

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# APPENDIX

# SAMPLE HAZARDOUS MATERIALS

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## Table 6-1
## Incompatible Chemicals in Storage, Use, or Handling

| Chemical | Incompatible With |
|---|---|
| Acetic acid | Azides, chromic acid, chromium, cumene hydroperoxide, cyanides, ethylene glycol, fluorine, hydroxyl compounds, nitric acid, nitrites, perchloric acid, peroxides, permanganates, hypochlorites, potassium chlorate, potassium perchlorate, sulfides |
| Acetic acid (glacial) | Azides, chromic acid, chromium, cumene hydroperoxide, cyanides, ethylene glycol, fluorine, hydroxyl compounds, nitric acid, nitrites, perchloric acid, peroxides, permanganates, hypochlorites, potassium chlorate, potassium perchlorate, sodium peroxide, sulfides |
| Acetic anhydride | Fluorine, perchloric acid, sodium peroxide |
| Acetone | Concentrated nitric and sulfuric acid mixtures, fluorine, hydrogen peroxide |
| Acetylene | Chlorine, bromine, copper, fluorine, silver, mercury, Iodine and their compounds |
| Acids | Ammonium nitrate, azides, cumene hydroperoxide, cyanides, fluorine, hypochlorites, nitrites, potassium chlorate, potassium perchlorate, sulfides |
| Air | Fluorine, phosphorous, white |
| Alcohol | Chromic acid, chromium, fluorine, hydrogen peroxide, perchloric acid, sodium peroxide |
| Alkalies | Water, carbon tetrachloride or other chlorinated hydrocarbons, carbon dioxide, halogens, fluorine, phosphorous, white |
| Alkali metals | Water, carbon tetrachloride or other chlorinated hydrocarbons, carbon dioxide, halogens, chlorates, fluorine, hydrocyanic acid, sulfuric acid |
| Alkaline metals (general) | Fluorine, hydrocyanic acid, sulfuric acid |
| (Powdered aluminum) | Water, carbon tetrachloride or other chlorinated hydrocarbons, carbon dioxide, halogens, ammonium nitrate, chlorates, chlorine, fluorine, hydrocyanic acid |
| (Powdered magnesium) | Water, carbon tetrachloride or other chlorinated hydrocarbons, carbon dioxide, halogens, ammonium nitrate, chlorates, chlorine, fluorine, hydrocyanic acid |
| Amines | Fluorine, nitroparaffins |
| Ammonia (anhydrous) | Mercury, bromine, chlorine, chlorine dioxide, calcium hypochlorite, fluorine, iodine, hydrogen fluoride, hydrofluoric acid (anhydrous), iodine |
| Ammonia (aqueous) | Bromine, chlorine dioxide, fluorine, hydrofluoric acid (anhydrous), iodine, mercury |
| Ammonium compounds | Silver |
| Ammonium nitrate | Acids, powdered metals, flammable liquids, fluorine, chlorates, nitrites, silver, sodium nitrite, sulfur, finely divided organic combustible materials |
| Ammonium salts | Chlorates, fluorine, silver, sodium nitrite |
| Aniline | Fluorine, nitric acid, hydrogen peroxide |
| Arsenical materials | Any reducing agents, fluorine |
| Azides | Acids, fluorine |
| Bases, inorganic | Fluorine, nitroparaffins |
| Benzaldehyde | Fluorine, sodium peroxide |
| Bismuth and its alloys | Fluorine, perchloric acid |
| Brass | Fluorine, nitric acid (concentrated) |
| Bromine | Acetylene, ammonia (anhydrous), fluorine, hydrocarbons, hydrogen, petroleum gases, sodium benzene, finely divided metals |
| Butadiene | Chlorine, Fluorine |

## Table 6-1 (cont'd)

| Chemical | Incompatible With |
|---|---|
| Calcium | Water, carbon tetrachloride or other chlorinated hydrocarbons, carbon dioxide, halogens, fluorine |
| Calcium hypochlorite | Ammonia (anhydrous), carbon (activated), fluorine |
| Calcium oxide | Water, fluorine |
| Camphor | Chromic acid, chromium, fluorine |
| Carbon (activated) | Calcium hypochlorite, fluorine, oxidizing agents, hypochlorites |
| Carbon dioxide | Alkalies, alkali metals, calcium, fluorine, lithium, potassium, sodium, lithium |
| Carbon disulfide | Fluorine, sodium peroxide |
| Carbon tetrachloride | Alkalies, alkali metals, calcium, fluorine, lithium, potassium, sodium, lithium |
| Chlorates | Ammonium nitrate, ammonium salts, acids, fluorine, powdered metals, sulfur, finely divided organic or combustible materials |
| Chlorine | Acetylene, Ammonia (anhydrous), benzene, butadience, butane, finely-divided metals, fluorine, hydrogen, methane, propane, sodium carbide, turpentine, hydrocarbons |
| Chlorine dioxide | Ammonia, fluorine, methane, phosphine, hydrogen sulfide |
| Chlorinated hydrocarbons | Alkalies, alkali metals, calcium, lithium, potassium, sodium, lithium |
| Chromic acid | Acetic acid, acetic acid (glacial), azides, naphthalene, camphor, cumene hydroperoxide, cyanides, glycerol, glycerin, alcohol, flammable liquids in general, fluorine, hydrocarbons, hypochlorites, nitrites, potassium chlorate, potassium perchlorate, sulfides, turpentine |
| Chromium | Acetic acid, azides, naphthalene, camphor, fluorine, glycerol, alcohol, flammable liquids in general, hydrogen peroxide |
| Combustible substance (finely divided) | Chlorates, fluorine, hydrogen peroxide |
| Copper | Acetylene, fluorine, hydrogen peroxide, nitric acid (concentrated) |
| Cumene hydroperoxide | Acids, fluorine |
| Cyanides | Acids, fluorine |
| Ethyl acetate | Fluorine, sodium peroxide |
| Ethyl alcohol | Fluorine |
| Ethylene glycol | Acetic acid, fluorine, potassium permanganate, sodium peroxide |
| Flammable liquids | Ammonium nitrate, chromic acid, chromium, fluorine, hydrogen peroxide, nitric acid, sodium peroxide, halogens |
| Flammable gases | Fluorine, nitric acid (concentrated), oxygen |
| Flammable substances | Fluorine, oxygen |
| Fluorine | All other chemicals |
| Fulminic acid | Azides, cumene hydroperoxide, cyanides, fluorine, hypochlorites, mercury, nitrites, potassium chlorate, potassium perchlorate, silver, sulfides |
| Furfural | Fluorine, sodium peroxide |
| Glycerin | Chromic acid, fluorine, potassium permanganate, sodium peroxide |
| Glycerol | Chromic acid, chromium, fluorine |
| Halogens | Alkalies, alkali metals, calcium, flammable liquids, fluorine lithium, potassium, sodium |
| Hydrocarbons (Butane) | Bromine, chlorine, chromic acid, fluorine, sodium peroxide, oxygen |
| (Benzene) | Ammonium nitrate, bromine, chlorine, chromic acid, fluorine, sodium peroxide, oxygen |
| (Gasoline) | Ammonium nitrate, bromine, chlorine, chromic acid, fluorine, sodium peroxide, oxygen |

## Table 6-1 (cont'd)

| Chemical | Incompatible With |
|---|---|
| (Grease) | Fluorine, oxygen, perchloric acid |
| (Diesel) | Ammonium nitrate, bromine, chlorine, chromic acid, fluorine, oxygen, sodium peroxide |
| (Methane) | Bromine, chlorine, chlorine dioxide, chromic acid, fluorine, oxygen, sodium peroxide |
| (Propane) | Bromine, chlorine, chlorine dioxide, chromic acid, fluorine, oxygen, sodium peroxide |
| (Grease) | Fluorine, oxygen, perchloric acid |
| (Diesel) | Ammonium nitrate, bromine, chlorine, chromic acid, fluorine, oxygen, sodium peroxide |
| (Methane) | Bromine, chlorine, chlorine dioxide, chromic acid, fluorine, oxygen, sodium peroxide |
| (Propane) | Bromine, chlorine, chlorine dioxide, chromic acid, fluorine, oxygen, sodium peroxide |
| Hydrocyanic acid | Alkalies, azides, cumene hydroperoxide, cyanides, fluorine, nitric acid, hypochlorites, nitrites, potassium chlorate, potassium perchlorate, sulfides |
| Hydrofluoric acid (anhydrous) | Ammonia (anhydrous), ammonia (aqueous), azides, cumene hydroperoxide, cyanides, fluorine, hypochlorites, nitrites, potassium chlorate, potassium perchlorate, sulfides |
| Hydrogen | Bromine, chlorine, fluorine, iodine |
| Hydrogen fluoride | Fluorine |
| Hydrogen peroxide | Aniline, copper, flammable liquids, fluorine, chromium, iron, most metals and their salts, alcohols, acetone, organic materials, aniline, nitromethane, flammable or combustible materials |
| Hydrogen sulfide | Chlorine dioxide, fluorine, fuming nitric acid, oxidizing gases |
| Hypochlorites | Fluorine, acids, activated carbon |
| Hydroxl compounds | Acetic acid, fluorine |
| Iodine | Acetylene, ammonia (anhydrous), ammonia (aqueous), fluorine, hydrogen |
| Iron | Fluorine |
| Lithium | Water, carbon tetrachloride or other chlorinated hydrocarbons, carbon dioxide, halogens, fluorine, sulfuric acid |
| Mercury | Acetylene, Ammonia (anhydrous), fluorine, fulminic acid, oxalic acid |
| Metals, powders or finely divided | Ammonium nitrate, bromine, chlorates, chlorine, fluorine, hydrogen peroxide |
| Metals, heavy | Fluorine, hydrogen peroxide, nitric acid (concentrated) |
| Methyl acetate | Fluorine, sodium peroxide |
| Methyl alcohol | Fluorine |
| Naphthalene | Chromic acid, chromium, fluorine |
| Nitrates | Fluorine, sulfuric acid |
| Nitric acid (concentrated) | Acetic acid, acetone, aniline, azides, brass, chromic acid, copper, cumene hydroperoxide, cyanides, flammable liquids, flammable gases, fluorine, heavy metals, hydrocyanic acid, hydrogen sulfide, hypochlorites, nitrites, potassium chlorate, potassium perchlorate, sulfides |
| Nitric acid (fuming) | Acetic acid, aniline, azides, cumene hydroperoxide, cyanides, flammable liquids, fluorine, hydrocyanic acid, hydrogen sulfide, hypochlorites, nitrites, potassium chlorate, potassium perchlorate, sulfides |
| Nitrites | Acids, ammonium nitrate, fluorine, potassium chlorate |
| Nitromethane | Fluorine, hydrogen peroxide |
| Nitroparaffins | Amines, bases (inorganic), fluorine |

## Table 6-1 (cont'd)

| Chemical | Incompatible With |
|---|---|
| Organic peroxides | Fluorine |
| Organic substance (finely divided) | Ammonium nitrate, chlorates, fluorine, hydrogen peroxide, potassium chlorate |
| Oxalic acid | Cumene hydroperoxide, cyanides, fluorine, hypochlorites, mercury, nitrites, silver, potassium chlorate, potassium perchlorate, sulfides |
| Oxygen | Carbon (activated), fluorine, grease, hydrogen, flammable liquids, solids or gases, oils, phosphorous, white |
| Oxidizers (solid, liquid, gas) | Carbon (activated), fluorine, hydrogen sulfide |
| Paper | Fluorine, perchloric acid |
| Perchloric acid | Acetic acid, acetic anhydride, alcohol, azides, bismuth and its alloys, cumene hydroperoxide, cyanides, fluorine, grease, hypochlorites, nitrites, oils, paper, wood, potassium chlorate, potassium perchlorate, sulfides |
| Permanganates | Acetic acid, fluorine |
| Peroxides (organic) | Acetic acid, acids (organic or mineral), fluorine [avoid friction, store cold] |
| Phosphine | Chlorine dioxide, fluorine |
| Phosphorous, white | Air, alkalies, fluorine, oxygen, reducing agents |
| Phosphorous pentoxide | Fluorine, water |
| Potassium | Water, carbon tetrachloride or other chlorinated hydrocarbons, carbon dioxide, halogens, fluorine, water |
| Potassium chlorate | Fluorine, sulfuric and other acids, any organic materials |
| Potassium perchlorate | Fluorine, sulfuric and other acids |
| Potassium permanganate | Ethylene glycol, fluorine, glycerin, sulfuric and other acids |
| Reducing agents | Arsenical materials, fluorine, phosphorous, white selenides |
| Selenides | Fluorine, reducing agents |
| Silver | Acetylene, ammonium compounds, fluorine, fulminic acid, oxalic acid, tartaric acid |
| | Water, carbon tetrachloride or other chlorinated hydrocarbons, carbon dioxide, halogens, fluorine |
| Sodium benzene | Bromine, fluorine |
| Sodium carbide | Chlorine, fluorine |
| Sodium nitrite | Ammonium nitrate and other ammonium salts, fluorine |
| Sodium peroxide | Acetic acid (glacial), acetic anhydride, benzaldehyde, carbon disulfide, ethyl acetate, ethyl or methyl alcohol, ethylene glycol, flammable liquids, fluorine, furfural, glycerin, hydrocarbons, methyl acetate |
| Sulfides | Acids, fluorine |
| Sulfur | Ammonium nitrate, chlorates, fluorine |
| Sulfuric acid | Acetone, azides, cumene hydroperoxide, cyanides, fluorine, hypochlorites, lithoium, nitrites, potassium chlorate, potassium perchlorate, potassium permanganate, sodium, sulfides |
| Tartaric acid | Azides, cumene hydroperoxide, cyanides, fluorine, hypochlorites, nitrites, potassium chlorate, potassium perchlorate, silver, sulfides |
| Turpentine | Chlorine, chromic acid, fluorine |
| Water | Alkalies, alkali metals, calcium, calcium oxide, lithium, potassium, sodium, lithium, fluorine |
| Wood | Fluorine, perchloric acid, phosphorous pentoxide |

## Table 6-2
## Common Corrosives

| Chemical Class | Solid | Liquid | Gas |
|---|---|---|---|
| **Inorganic Acids** | Metaphosphoric | Sulfuric, Phosphoric, Hydrochloric, Hydrofluoric | Hydrogen fluoride, Hydrogen chloride, Hydrogen bromide |
| **Organic Acids** | Oxalic, Trichloroacetic | Glacial acetic, Propionic, Formic | No Listing |
| **Bases (Alkalis)** | Sodium hydroxide, Potassium hydroxide | Aqueous Ammonia, | Ammonia |
| **Halogens** | Iodine | Bromine | Chlorine, Fluorine |
| **Oxidizers** | Sodium nitrate, Potassium permanganate | Perchloric acid, Nitric acid | Chlorine, Fluorine |
| **Dehydrating Agents (Anhydrides)** | Sodium hydroxide | Acetic anydride | Anhydrous ammonia |
| **Organic Halides and Organic Acid Halides** | No listing | Acetyl chloride, Benzoyl chloride, | Carbonyl chloride |
| **Halogen Salts** | Aluminum chloride, Zinc chloride | Thionyl chloride | No listing |
| **Others** | No listing | Mercury, Hydrazine | No listing |

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**Table 6-3**
**Chemicals with Oxygen-Containing Groups**

| Chemical Group | Chemical Formula |
|---|---|
| Peroxides | $O_2^{-2}$ |
| Nitrates | $NO_3^-$ |
| Nitrites | $NO_2^-$ |
| Perchlorates | $ClO_4^-$ |
| Chlorates | $ClO_3^-$ |
| Chlorites | $ClO_2^-$ |
| Hypochlorites | $ClO^-$ |
| Dichromates | $Cr_2O_7^{-2}$ |
| Permanganates | $MnO_4^-$ |
| Persulfates | $S_2O_8^{-2}$ |

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**Table 6-4**
**Oxidizers by Class**

| Class | Examples |
|---|---|
| 1 | Aluminum nitrate<br>Potassium dichromate<br>Ammonium persulfate<br>Potassium nitrate<br>Barium chlorate<br>Potassium persulfate<br>Barium nitrate<br>Silver nitrate<br>Barium peroxide<br>Sodium Carbonate peroxide<br>Calcium chlorate<br>Sodium dichloro-s-triazinetrione<br>Calcium nitrate<br>Sodium dichromate<br>Calcium peroxide<br>Sodium nitrate<br>Cupric nitrate<br>Sodium nitrite<br>Hydrogen peroxide (8 to 27.5 percent)<br>Sodium perborate<br>Lead nitrate<br>Sodium perborate tetrahydrate<br>Lithium hypochlorite<br>Sodium perchlorate monohydrate<br>Lithium peroxide<br>Sodium persulfate<br>Magnesium nitrate<br>Strontium chlorate<br>Magnesium perchlorate<br>Strontium nitrate<br>Magnesium peroxide<br>Strontium peroxide<br>Nickel nitrate<br>Zinc chlorate<br>Nitric acid (<70 percent concentrated)<br>Zinc peroxide<br>Perchloric acid (<60 percent concentrated) |

## Table 6-4 (cont'd)

| Class | Examples |
|---|---|
| **2** | Calcium hypochlorite (<50 percent weight)<br>Potassium permanganate<br>Chromium trioxide (chromic acid)<br>Sodium chlorite (<40 percent weight)<br>Halane<br>Sodium peroxide<br>Hydrogen peroxide (27.5 to 52 percent concentrated)<br>Sodium permanganate<br>Nitric acid (>70 percent concentrated)<br>Trichloro-s-triazinetrione |
| **3** | Ammonium dichromate<br>Potassium chlorate<br>Hydrogen Peroxide (52 to 91 percent concentrated)<br>Potassium dichloroisocyanurate<br>Calcium hypochlorite (>50 percent weight)<br>Sodium chlorate<br>Perchloric acid (60 to 72.5 percent concentrated)<br>Sodium chlorite (>40 percent weight)<br>Potassium bromate<br>Sodium dichloro-s-triazinetrione |
| **4** | Ammonium perchlorate<br>Ammonium permanganate<br>Guanidine nitrate<br>Hydrogen peroxide (>91 percent concentrated)<br>Perchloric acid (>72.5 percent)<br>Potassium superoxide |

**Table 6-5**
**Toxicity Terminology**

| Value | Abbreviation | Definition |
|---|---|---|
| Threshold Limit Value | TLV | Refers to airborne concentrations of substances and represents conditions under which it is believed that nearly all workers may be exposed repeatedly, day after day, without adverse effect. |
| Threshold Limit Value/Time-Weighted Average | TLV/TWA | The time-weighted average concentration for a normal 8-hour workday and a 40-hour workweek, to which nearly all workers may be exposed repeatedly, day after day, without adverse effect. |
| Threshold Limit Value/Short-Term Exposure Limit | TLV/STEL | The concentration to which workers can be exposed continuously for a short period of time without suffering from: 1) irritation, 2) chronic or reversible tissue damage, or 3) narcosis of sufficient degree to increase the likelihood of accidental injury, impair self-rescue, or materially reduce work efficiency, and provided that the daily TLV/TWA is not exceeded. |
| Threshold Limit Value Ceiling | TLV-C | The concentration that should not be exceeded during any part of the working exposure. |
| Permissible Exposure Limit | PEL | Same as TLV/TWA. |
| Immediately Dangerous to Life and Health | IDLH | A maximum concentration (in air) from which one could to escape within 30 minutes without any escape-impairing symptoms or any irreversible health effects. |
| Recommended Exposure Limit | REL | Highest allowable airborne concentration that is not expected to injure a worker, expressed as a ceiling limit or TWA for an 8- or 10-hour workday. |

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## Table 6-6
## Common and Highly Toxic Chemicals

| | | |
|---|---|---|
| Acetic anhydride | Acrolein | Acrylamide |
| Allyl alcohol | Allyl chloride | Aniline |
| Antimony compounds | Anisidines | Arsenic compounds |
| Soluble barium salts | p-benzoquinone | Benzoyl peroxide |
| Benzoyl chloride | Beryllium and its compounds | Boron tribromide |
| Boron trifluoride | Bromine | Butylamines |
| Chlorine | Chloronitrobenzenes | Chromium compounds |
| Cresols | Cyanides | Diazomethane |
| N,N-dimethylaniline | Dimethyl sulfate | Epichlorohydrin |
| Ethanolamine | Ethylene chlorohydrin | Fluorine |
| Formaldehyde | Formic acid | Hydrazine |
| Hydrochloric acid | Hydrofluoric acid | Hydrogen cyanide |
| Hydrogen peroxide | Indium salts | Iodine |
| Iodomethane | Isocyanates | Maleic anhydride |
| Mercaptans | Mercury and mercury compounds | Nickel carbonyl |
| Nitric acid | Nitrobenzene | Nitro compounds |
| Osmium salts | Oxalic acid | Ozone |
| Phenol | Phenylene diamines | Phenyl hydrazine |
| Phosgene | Phosphorus pentachloride | Phosphorus pentasulfide |
| Phosphorus trichloride | Phthalic anhydride | Propylamines |
| Pyridine | Selenium compounds | Soluble silver salts |
| Sodium-mercury amalgam | Sulfur dioxide | Tellurium compounds |
| Thallium compounds | Tetrachlorethane | Organotin compounds |
| Toluidines | Xylidines | |

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# *UNIT 7:*
# *FIRE MODELING CONCEPTS*

***OBJECTIVE***

*The students will explain how fire and egress modeling can be used in the fire and life safety design and evaluation of the built environment.*

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## INTRODUCTION

The term "model" can be defined in many ways, ranging from a "miniature representation of an object" to "a system of postulates, data, and inferences presented as a mathematical description of an entity or state of affairs." Fire effects models are basic to development and evaluation of equivalences and performance-based designs. In the field of fire protection, a fire effects model is defined as a structured approach to predicting one or more effects of a fire.

## FIRE EFFECTS MODELING PROGRAMS

While fire effects modeling programs have been available for a number of years, their widespread practical use has been somewhat limited in conjunction with the prescriptive codes. Performance-based codes and performance-based designs, however, will rely heavily on the application and use of the various fire effects modeling programs.

Fire effects modeling can be done using only hand calculations or can use complex computer-based programs. Regardless of their complexity, these models incorporate engineering, engineering judgment, and scientific principles in the analysis of fire and fire effects. Models can be used to simulate or, some would say, predict the characteristics and conditions of a specific fire under specified conditions. Regardless of the model used, it must be appropriate for the specific fire scenario(s). One always must remember that the fire effects model is providing results in very specific terms that must be evaluated against "real world" conditions.

Fire effects models simulate fire scenarios and incorporate conditions that define the development of a fire and the spread of combustible products. They are based on safety goals agreed on by all the stakeholders. They are not intended to analyze fire behavior in spaces that are outside of the prescribed limits of the models' intended dimensions.

Fire characteristics simulated in fire effects models include

- gas/surface temperature;
- flow rates of gas;
- heat flux;
- smoke obscuration;
- toxic gas movement;
- building elements;
- activation time for sprinklers/detectors; and
- various fire parameters.

### Fire Models

A fire model is a specific set of conditions that defines the development of fire, the spread of combustion products throughout a building or portion of a building, the reactions of people to

fire, and the effects of combustion products. Design fire models are those that are used for the evaluation of a proposed design. All stakeholders must agree upon the fire and design fire models.

The various fire effects models can be used to simulate or predict conditions such as gas and surface temperatures, gas flow through openings, heat flux, smoke obscuration, and toxic gas production. Models also can be used to predict the effects of heat on structural elements and activation times for automatic sprinklers and smoke and heat detectors.

## FIRE EFFECTS MODELS

There are two types of fire effects models: Zone models, and field models.

### Zone Models

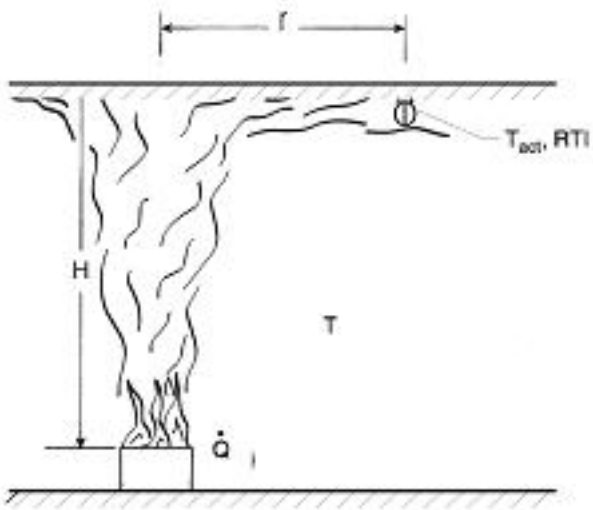
Zone models simplify the fire environment within the compartment(s). This type of model divides the compartment into zones. Most models have two zones: the upper layer or hot gas or smoke zone; and the lower layer, or cooler zone.

The model assumes each zone has a uniform temperature and gas concentrations mix. During model execution, the bottom of the hot layer descends over time into the compartment(s), as a direct function of the predicted heat-release rate (HRR) and ventilation factors. The temperature of upper and lower layers and various surfaces, such as the ceiling and floor, also can be predicted.

Zone models may be developed for implementation with either hand calculators or computer-based software programs, with computer programs being the more common approach. Because of some of the assumptions built into the models regarding heat transfer and other conditions, there can be legitimate questions as to the relevance of each model to reflect actual fire conditions.

Zone models currently available from National Institute of Standards and Technology (NIST) include DETACT, CFAST and FPETool. DETACT predicts detector/sprinkler activation. FPETool outputs include layer temperatures and height and thermal activation for a single compartment. CFAST provides the same type of outputs as FPETool, but can handle up to 30 compartments. As in all fire effects models, HRR is an input, and they all assume smooth, flat, and unconfined ceilings.

CFAST Version 6 also can be used in conjunction with **Smokeview**. **Smokeview** will be discussed later in this unit.




## Zone Model Limitations

Zone models assume horizontal, smooth ceilings. Relative compartment dimensions are restricted, and door and window locations cannot be specified. They also do not model interior finish flame spread, or ignitability from smoldering; fire suppression is not fully modeled.

## Computational Fluid Dynamics Models

Computational Fluid Dynamics (CFD) models are much more complex than zone models and require the use of more powerful computers. These divide the fire compartment(s) into thousands of small rectangular cells. The models then will predict the density, velocity, temperature, pressure, and concentration of the fire gases in each cell. They compute gas movement based on the laws of mass, momentum, and energy. While these models can provide a more detailed analysis, they also make some simplifying assumptions and have limitations.

## Fire Dynamic Simulator Models

The NIST Fire Dynamics Simulator (FDS) consists of two programs, **FDS** and **Smokeview**.

**FDS** predicts smoke and/or air flow movement caused by fire, wind, ventilation systems, etc. It uses material properties of fuel to simulate fire growth.

**Smokeview** visualizes or converts the data from the predictions generated by the FDS to a color graphic visual representation. **Smokeview** visualizes FDS-computed data by animating time-dependent particle flow, two-dimensional slice contours, and surface boundary contours. Data at a particular time also may be visualized using two-dimensional or three-dimensional contour plots or vector plots.

## Fire Effects Model Limitations

Every modeling program or approach has limitations. As noted previously, in zone models, the room geometry is based on smooth, flat ceilings, with doors and windows at fixed locations. The combustible nature and flame spread of interior finish materials is not included in fire growth calculations.

CFD fire effects models cannot calculate the ignitability of objects from small flames or the spread of fire over surfaces. The effects of fire suppression systems also are not fully modeled, and no NIST model is available for non-water-based fire suppression systems.

It is important for the code official to understand the limitations that exist with fire effects modeling. These limitations are reflected in the disclaimer that NIST publishes with all fire effects modeling software. In general, this disclaimer states that the program is intended to be used only by those competent in the field of fire safety and, in some instances, the fields of fluid dynamics, thermodynamics, combustion, and heat transfer. The model is intended only to supplement the informed judgment of the qualified user.

Computer modeling may or may not have predictive capability when applied to a specific set of factual circumstances. Lack of accurate predictions by the model could lead to erroneous conclusions with regard to fire safety. All fire effects modeling results should be evaluated by an informed user.

Models are not intended to analyze fire behavior spaces that are outside the prescribed limits or intended dimensions of the models.

## Fire Effects Modeling Using Calculators

Some modeling can be done without the use of computers. Hand calculators can be used in a simple fire environment to predict initial growth rate, steady burning rate, peak heat release rate, flame height, flame temperature, and fire plume velocity. Many examples of hand calculations can be found in *The SFPE Handbook of Fire Protection Engineering*.

## Models--Points to Consider

In evaluating a performance-based design that uses fire effects models, an AHJ should ask these questions:

- How does the model work?
- On what design is it based?
- What assumptions does the model make?

- Are the model assumptions consistent with your fire scenario?
- Is the model sensitive to small changes, in particular input scenarios?
- Are the hypotheses tested consistent with the scenarios and acceptance criteria established by the stakeholders?
- Are the timelines used consistent with timelines for critical fire events established by the stakeholders?
- What happens if the bounding conditions change or if the model assumptions change?

### Additional Resources

For further information on fire effects modeling, read "Introduction to Fire Effects Modeling" in Section 11, Chapter 4 of the NFPA *Fire Protection Handbook*, or visit the NIST Web site at www.nist.gov. There, you can find more than 600,000 articles on fire effects modeling, burn test and experiment data, videos, downloadable models, and recreations of fire incidents.

The use of fire effects and egress models in the context of performance-based designs are covered in more depth in the 6-day National Fire Academy (NFA) course *Evaluating Performance-Based Designs*. The 2-week NFA course *Fire Dynamics/Fire Modeling* covers the actual data input and use of the FDS and Smokeview.

## EGRESS MODELS

### Human Factors in Models

An essential, if not the most critical, component of any modeling evaluation is fire-related human behavior, or the human factor. All modeling and performance-based design must take into account physiological and behavioral responses to fire. In every fire scenario there is the human factor in the ignition of the unwanted fire, whether it be through intent or carelessness. How the occupants of a building react under fire conditions also has a direct impact on the outcome. Inappropriate actions can make the situation worsen or affect the effectiveness of fire safety systems.

Egress models variables can include the number of occupants, their distribution in the building, the complexity of the egress route, occupant movement through openings, their susceptibility to products of combustion and ADA *Accessibility Guidelines* requirements.

#### Problems in Modeling Human Behavior

The study of fire-related human behavior has in the past been affected by several problems. Obviously, experimental subjects cannot be placed in actual fire scenarios, and after-the-fact

information from witnesses may contain errors. Research has concentrated on the behaviors exhibited by persons in fires, from their first awareness of a possible problem through completion of the evacuation process. Data has been accumulated through indepth case studies and statistical, summary studies of large numbers of incidents.

Egress models cannot include

- occupant characteristics;
- familiarity with the building;
- mobility/effect of crowding;
- movement through smoke;
- audibility of alarm in ambient noise;
- training and instructions;
- response to cues;
- decisionmaking;
- distribution of exits; and
- results if an exit is compromised.

## Modeling Programs

Modeling programs are available as part of FPETool, Hazard I, and other models to calculate egress times and the tenability limits of various fire gases and oxygen depletion. The stand-alone egress models, such as Pathfinder and EVACNET, provide minimum time to egress from a building. While these predictions can be made, what remains most unpredictable is the human factor. In these various modeling programs variables such as the number of occupants, their distribution within the building, the complexity and capacity of the egress system, and the susceptibility of the occupants to the products of combustion are considered.

## Limitations of Egress Models

While these are important factors, equally important, but not considered or included in the models, are characteristics of the occupants (age, physical condition, sleeping, awake, etc.); the familiarity of the occupants with the building; the audibility of the alarm signal; and the actual reaction of the occupants to the alarm signal or fire conditions such as oxygen deprivation, heat, gases, power failure, or smoke obscuration. The models recognize and validate the fire threat, evaluate the actual danger, and then act on the evaluation.

This is an area where the AHJ needs to ask a lot of "what if" questions. The underlying questions are, How can or will the design compensate for the lack of proper response by the occupants? What if the alarm is not heard? What id the occupants don't respond promptly? The active and passive fire protection features of a building must be designed to protect the occupants from themselves. Designs that rely heavily upon the human factor for acceptable outcome are clearly questionable. Designs must consider the effectiveness and reliability of evacuation training and accountability systems realistically.

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# APPENDIX

# JOB AIDS

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## Job Aid 7.1

## Fire Modeling Programs Available from National Institute of Science and Technology (NIST) www.NIST.gov (301) 975-6850 100 Bureau Drive, Stop 8600 Gaithersburg, MD 20899-3460

**ALOFT-FTTM (A Large Outdoor Fire Plume Trajectory Model--Flat Terrain)**
A computer-based model to predict the downwind distribution of smoke particulate and combustion products from large outdoor fires. It solves the fundamental fluid dynamic equations for the smoke plume and its surroundings with flat terrain. The program contains a graphical user interface for input and output and a user-modifiable database of fuel and smoke emission parameters. The output can be displayed as downwind, crosswind, and vertical smoke concentration contours.

**ASCOS (Analysis of Smoke-Control Systems)**
A computer program for steady air flow analysis of smoke-control systems. This program can analyze any smoke-control system that produces pressure differences with the intent of limiting smoke movement in building fire situations. The program also is capable of modeling the stack effect created in taller buildings during extreme temperature conditions. The program input consists of the outside and building temperatures, a description of the building flow network, and the flows produced by the ventilation or smoke-control system. The output consists of the steady-state pressures and flows throughout the building.
***Limitations: Assumes steady-state air flow. Cannot account for changes in the building or air handling system during a fire.***

**ASET-B (Available Safe Egress Time--BASIC)**
A program for calculating the temperature and position of the hot smoke layer in a single room with closed doors and windows. ASET-B is a compact easy-to-run program, which solves the same equations as ASET. The required program inputs are a heat-loss fraction, the height of the fire, the room ceiling height, the room floor area, the maximum time for the simulation, and the rate of heat release of the fire. The program outputs are the temperature and thickness of the hot smoke layer as a function of time.
***Limitations: Based upon a single compartment with no openings. Does not provide species concentrations or time to detection.***

**ASMET (Atria Smoke Management Engineering Tools)**
Consists of a set of equations and a zone fire model for analysis of smoke management systems for large spaces such as atria, shopping malls, arcades, sports arenas, and exhibition halls.

**BREAK1 (Berkeley Algorithm for Breaking Window Glass in a Compartment Fire)**
A program that calculates the temperature history of a glass window exposed to user-described fire conditions. The calculations are stopped when the glass breaks. The inputs required are the glass thermal conductivity, thermal diffusivity, absorption length, breaking stress, Young's modulus, thermal coefficient of linear expansion, thickness, emissivity, shading thickness, half-width of window, the ambient temperature, numerical parameters, and the time histories of flame radiation from the fire, hot layer temperature and emissivity, and heat transfer coefficients. The outputs are temperature history of the glass normal to the glass surface and the window breakage time.

**CCFM (Consolidated Compartment Fire Model version VENTS)**
A two-layer zone-type compartment fire model computer code. It simulates conditions due to user-specified fires in a multiroom, multilevel facility. The required inputs are a description of room geometry and vent characteristics (up to 9 rooms, 20 vents), initial state of the inside and outside environment, and fire energy release rates as a function of time (up to 20 fires). If simulation of concentrations of products of combustion is desired, then product release rates must also be specified (up to three products). Vents can be simple openings between adjacent spaces (natural vents) or fan/duct forced ventilation systems between arbitrary pairs of spaces (forced vents). For forced vents, flow rates and direction can be user-specified or included in the simulation by accounting for user-specified fan and duct characteristics. Wind and stack effects can be taken into account. The program outputs for each room are pressure at the floor, layer interface height, upper/lower layer temperature, and (optionally) product concentrations.

**CCFMPLT**
A graphics program that runs in conjunction with CCFM. The results from CCFM are sent to a user-specified data file at each prescribed time step. CCFMPLT plots these data on an IBM-PC-compatible microcomputer and optionally can provide hardcopy output.

**CFAST**
A zone model that predicts the effect of a specified fire on temperatures, various gas concentrations, and smoke layer heights in a multicompartment structure.
***Limitations: Assumes flat horizontal ceilings.***

**DETACT-QS (DETector ACTuation--Quasi Steady)**
A program for calculating the actuation time of thermal devices below unconfined ceilings. It can be used to predict the actuation time of fixed-temperature heat detectors and sprinkler heads subject to a user-specified fire. DETACT-QS assumes that the thermal device is located in a relatively large area, that is, only the fire ceiling flow heats the device and there is no heating from the accumulated hot gases in the room. The required program inputs are the height of the ceiling above the fuel, the distance of the thermal device from the axis of the fire, the actuation temperature of the thermal device, the response-time index (RTI) for the device, and the rate of heat release of the fire. The program outputs are the ceiling gas temperature and the device temperature both as a function of time and the time required for device actuation.

**DETACT-T2 (DETector ACTuation--Time squared)**
A program for calculating the actuation time of thermal devices below unconfined ceilings. It can be used to predict the actuation time of fixed temperature and rate-of-rise heat detectors, and sprinkler heads subject to a user-specified fire that grows as the square of time. CT-T2 assumes that the thermal device is located in a relatively large area, that is, only the fire ceiling flow heats the device and there is no heating from the accumulated hot gases in the room. The required program inputs are the ambient temperature, the response time index (RTI) for the device, the activation and rate-of-rise temperatures of the device, height of the ceiling above the fuel, the device spacing, and the fire growth rate. The program outputs are the time to device activation and the heat release rate at activation.

**ELVAC (Elevator Evacuation)**
An interactive computer program that estimates the time required to evacuate people from a building with the use of elevators and stairs. It is cautioned that elevators generally are not intended as a means of fire evacuation, and they should not be used during fires. However, it is possible to design elevator systems for fire emergencies, and ELVAC can be used to evaluate the potential performance of such systems. ELVAC calculates the evacuation time for one group of elevators. If a building has more than one group of elevators, ELVAC can be run on each group separately. Input consists of floor-to-floor heights, number of people on floors, number of elevators in the group, elevator speed, elevator acceleration, elevator capacity, elevator door type and width, and various inefficiency factors. The output is a table of elevator travel time, round-trip time, people moved, and number of round trips for each floor, plus the total evacuation time.

**FASTLite**
A user-friendly software package that builds on the core routines of FPETool and the computer model CFAST to provide calculations of fire phenomena for use by the building designer, code official, fire protection engineer, and fire-safety related practitioner.
***Limitations: Models up to three compartments with flat horizontal ceilings with multiple openings. Assumes a user-specified fire in one of the compartments.***

**FIRDEMND**
Simulates the suppression of postflashover charring and noncharring solid-fuel fires in compartments using water sprays from portable hose-nozzle equipment used by the fire departments. The output of the Fire Demand Model (FDM) shows the extinguishing effects of water spray at various flow rates and droplet sizes. The calculations are based on a heat and mass balance accounting for gas and surface cooling, steam-induced smothering, water-spray induced air entrainment, direct extinguishment of the fire by water, and the energy transport via inflow and outflow of heat and products of combustion.
***This model can be complicated, but it is very powerful.***

**FIRST (FIRe Simulation Technique)**
The direct descendant of the HARVARD V program developed by Howard Emmons and Henri Mitler. The fire may be entered either as a user-specified time-dependent mass loss rate or in terms of fundamental properties of the fuel. In the latter case, the program will predict the fire growth rate by considering the changing oxygen concentration and smoke layer conditions in the room of fire origin. It also can predict the heating and possible ignition of up to three targets. The original fire and targets also may be user-specified fires. The required program inputs are the geometric data describing the rooms and openings and the thermophysical properties of the ceiling, walls, burning fuel, and targets. The generation rate of soot must be specified, and the generation rates of other species may be specified as a yield of the pyrolysis rate. Among the program outputs are the temperature and thickness of, and species concentrations in, the hot upper layer and also in the cooler, lower layer in each compartment. Also given are wall surface temperatures, heat transfer rates, and mass flow rates.

**MASBANK**
Used to create and maintain a database of materials and their fire properties for use by the FIRST program. MASBANK can accommodate 20 properties for up to 50 materials. The program has the capability to add, delete, change, alphabetize, and view the material properties in the data bank. Material properties from MASBANK may be transferred directly into the FIRST program. MASBANK is written in FORTRAN.

**FPETool**
A set of engineering equations useful in estimating potential fire hazard and the response of the space and fire protection systems to the developing hazard. Version 3.2 incorporates an estimate of smoke conditions developing within a room receiving steady-state smoke leakage from an adjacent space. Estimates of human viability resulting from exposure to developing conditions within the room are calculated based on the smoke temperature and toxicity.
***Limitations: Based on a single compartment. Each FPETool routine also has its own limitations.***

**LAVENT**
A program developed to simulate the environment and the response of sprinkler links in compartment fires with draft curtains and fusible-link-operated ceiling vents. The model, used to calculate the heating of the fusible links, includes the effects of the ceiling jet and the upper layer of hot gases beneath the ceiling. The required program inputs are the geometric data describing the compartment, the thermophysical properties of the ceiling, the fire elevation, the time-dependent energy release rate of the fire, the fire diameter or energy release rate per area of the fire, the ceiling vent area, the fusible link RTI and fuse temperature, the fusible link positions along the ceiling, the link assignment to each ceiling vent, and the ambient temperature. A maximum of 5 ceiling vents and 10 fusible links are permitted in the compartment.

The program outputs are the temperature, mass, and height of the hot upper layer, the temperature of each link, the ceiling jet temperature and velocity at each link, the radial temperature distribution along the interior surface of the ceiling, the radial distribution of the heat flux to the interior and exterior surfaces of the ceiling, the fuse time of each link, and the vent area that has been opened.
***Limitations: Models up to 5 vents and 10 fusible links in a single compartment.***

**GRAPH**
A graphics program that runs in conjunction with LAVENT. The results for LAVENT are sent to the data file, GRAPH.OUT, after each prescribed time step. GRAPH then allows the user to choose two sets of variables to be plotted on the screen and has the additional capability of hardcopy output.

**NIST Fire Dynamics Simulator and Smokeview**
The NIST Fire Dynamics Simulator predicts smoke and/or air flow movement caused by fire, wind, ventilation systems, etc. **Smokeview** visualizes the predictions generated by NIST FDS.

**HAZARD I**
Another fire modeling program available is HAZARD I, originally developed by the Building and Fire Research Laboratory at NIST. It is currently available for purchase from the National Fire Protection Association (NFPA).

The model provides a method for quantifying the hazards to occupants of buildings from fires, and the relative contribution of specific products to those hazards. The model combines fire prediction calculations and simulation of the decisions, actions, and progress of occupants during a specified fire.
***Limitations: Designed for residential structures. Other applications require a more detailed knowledge of the model.***

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## Job Aid 7.2

## Types of Fire Effects Models Used in Fire-Safe Building Designs

| Physical | | |
|---|---|---|
| **Model Type** | **Pros** | **Cons** |
| **Full-Scale Fire Experiments**<br><br>Example: Underwriters Laboratories (UL) or Factory Mutual (FM) Global high rack storage burn | • Potential to closely represent actual fire of interest | • Expensive<br>• Limited number, if any, replicate tests<br>• Limited experimental control<br>• Limits of test facility may not represent the fire<br>• Building, test uncertainties due to materials, weather, source of ignition |
| **Reduced Scale Experiments**<br><br>Examples: 2/5-scale fire compartment, saltwater modeling, cold smoke model at National Fire Academy (NFA) | • Less expensive than full scale<br>• Replicate testing<br>• Typically more parameters can be varied<br>• Better experimental control | • Physical fire properties do not scale the same<br>• Saltwater models or "cold smoke" models do not include heat transfer effects |
| **Mathematical** | | |
| **Model Type** | **Pros** | **Cons** |
| **Hand Calculations**<br><br>Examples: Flame height, minimum HRR for flashover | • Quick estimations<br>• No special equipment needed | • Considers only a limited part of total problem.<br>• Many assumptions behind the simplified algorithm<br>• Labor-intensive to study many different situations<br>• Usually address steady-state scenarios |
| **Computer Models**<br><br>Examples: DETACT, ASET-B, FDS | • Consider many factors together, fire properties as well as building geometry considerations, in order to predict the impact of interaction between the two<br>• Can address growing fire scenarios | • A good understanding of the physics and assumptions behind the computer program is needed<br>• Set up and run time on complicated models can be very time intensive |

## About Fire Effects Models

Types of computer-based fire effects models include zone models and field models.

### About Zone Models

In the simplest form, a zone model divides a single room into a "hot gas layer" and a "cool gas layer." The laws of conservation of mass and conservation of energy are taken on the "hot gas layer." In other words, a mass and energy balance needs to be accounted for on the hot gas layer. So the energy input from the fire to the hot gas layer must equal the energy in the hot gas layer, plus energy losses caused by heating the ceiling and walls of the room, and any losses of energy flowing out of open doors or windows.

The same is true of the mass added to the hot gas layer by the burning fuel. A two-layer zone model is well suited to modeling a rectangular compartment with a smooth, flat horizontal ceiling. Effectively, the two-zone model has one computational cell for each room modeled.

Zone models do not account for changes in pressure caused by a fire. Zone models do not predict the growth and development of a fire. The fire growth must be input into the model. The fire is considered as a "point source," a source of thermal energy that has no relation to the size or shape of the flames that would compose the "real" fire in a room.

Zone models use a "quasi-steady" assumption, which means that a change in the fire input at the source results in an instantaneous change to conditions in the hot gas layer. No transportation time is considered. Only one "characteristic temperature" will be predicted for the hot gas layer, though in reality, the temperature near the ceiling will be significantly hotter than the temperature near the lower edge of the hot gas layer.

### About Field Models

A field model or computational fluid dynamics model (CFD) has the capability of modeling compartments or buildings of various shapes and sizes, since the model can partition a room or building into thousands or hundreds of thousands of computational cells. In addition to using the laws of conservation of mass and energy, CFD models also use the laws of conservation of momentum and species to provide a more realistic and detailed description of the movement of fire gases and what they contain.

A gas temperature and velocity will be predicted for each computational cell at very small time intervals, yielding significant quantities of predicted values. These models usually are used with another program that can turn the numbers into a graphical output for analysis. The visualization programs typically use isotherms and vectors to describe model output in the same way that temperature and wind data are displayed on weather maps during the evening news.

## Job Aid 7.3

### A Sample of Computer Fire effects models and Their Properties

The chart below presents a cross representation of computer-based fire effects models, ranging from the simplest model (DETACT-QS) to the most complex (FDS/Smokeview). A list of the values that the model can predict, as well as a partial list of limitations, is given for each model to give the AHJ a sense of the capabilities of the models and the types of limitations each model has. Further information about each of the models can be found in the technical documentation for each of these models. The AHJ should ask for these documents when a design relying on a fire model is presented.

| Name of Model | Type | Predicts | Limitations |
|---|---|---|---|
| **DETACT-QS** | Empirical/Zone | • Ceiling jet temperature<br>• Heat detector activation time | • Smooth, flat, horizontal, unconfined ceiling<br>• Assumes maximum ceiling jet temperature.<br>• Input of fire HRR required |
| **ASET-B** | Zone | • Smoke layer temperature<br>• Smoke layer height above floor | • Smoke layer described by only one temperature and thickness<br>• Smooth, flat horizontal ceiling<br>• Single room with closed windows and doors with assumed leakage<br>• Fire assumed to be in center of room.<br>• Input of fire HRR required |

| Name of Model | Type | Predicts | Limitations |
|---|---|---|---|
| **FPETool Fire Simulator** | Zone | • Ceiling jet temperature<br>• Ceiling jet velocity<br>• Heat detector activation time<br>• Smoke layer temperature<br>• Smoke layer height above floor | • Smoke layer described by only one temperature<br>• Smooth, flat horizontal ceiling<br>• Fire assumed to be in center of room<br>• Input of fire HRR required |
| **FAST** | Zone | • Ceiling jet temperature<br>• Ceiling jet velocity<br>• Heat detector activation time<br>• Smoke layer temperature<br>• Smoke layer height above floor | • Smoke layer described by only one temperature<br>• Smooth, flat horizontal ceiling<br>• Input of fire HRR required |
| **FDS/Smokeview** | Field or CFD | • Simulates fire growth<br>• Heat detector activation time<br>• Gas temperature throughout modeled room or building<br>• Gas velocity throughout modeled room or building<br>• Tracks gas concentrations<br>• Wall and ceiling temperatures<br>• Limited suppression effects<br>• Good visualization of output | • Requires more detailed data<br>• Requires more expertise to use<br>• Labor-intensive<br>• Requires more computer power<br>• Limited database of material properties for input<br>• Models are still under development and are changing |

## Job Aid 7.4

## Checklist to Evaluate Appropriateness of Fire Effects Models

What is the fire scenario?

Does the fire model used include all the conditions that define the development of fire and its spread through all or parts of the building?

Does the fire model address each stakeholder safety goal?

How does the fire model simulate

- Structural failure of building elements
- Activation times for sprinklers and detectors
- Occupant egress times
- Production of toxic gases

What are the data on which the occupant egress behavior is based?

- Number of occupants
- Distribution in the building
- Stair widths
- Median width of doors
- Estimated time for occupants to evacuate
- Susceptibility of occupants to smoke and other toxicities

How are uncertainties addressed in the fire model?

- Building material variations
- Installation
- System and component variability
- Unanticipated uses of systems
- Unpredictable human action

Is the fire size realistic for the fire scenario?

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