CHAPTER 16

FIRE PROTECTION AND PREVENTION

16-1 INTRODUCTION

The Fire Problem

Each year, fire-related losses in the United States are considerable. There are approximately 1 million fires involving structures and approximately 8,000 deaths each year, and the total annual property loss exceeds $20 billion. These figures are conservative and do not include many indirect costs, such as litigation, investigation, and other costs borne by society.

Most deaths resulting from fires do not result from burns. Only approximately one fourth of fire-related deaths are the result of burns. Nearly two thirds of all fire-related deaths result from inhalation of carbon monoxide, smoke, toxic gases, and asphyxiation. Approximately one tenth of the deaths are from mechanical injuries, such as injuries from falls or falling material.

The overall death rate from fires is 2.8 per 100,000 population. The fire death rates for children younger than 5 years and adults older than 40 years exceeds the population average. Death rates increase exponentially with age for those older than 40 years. The death rate is 12.5 for those aged 75 to 85 years and 22.2 for those older than 85 years.

Studies have shown that deaths in fires are often alcohol related. In one study, evidence suggested that more than 80% of the victims had been consuming alcohol. Another study looked at age and blood alcohol level for fire victims. For those victims aged 30 to 60 years, approximately one quarter had no alcohol content in the blood and approximately two thirds had an alcohol content of more than 0.10%.

Most fatal fires involve one or two victims. However, large losses receive the greatest attention. The greatest losses have occurred in places of assembly. On December 30, 1903, 602 people died in the fire at Chicago's Iroquois Theater. On July 6, 1944, the Ringling Brothers and Barnum and Bailey Circus fire in Hartford, Connecticut, took 168 lives. There have been a number of famous fires in supper clubs, such as the fire at the Beverly Hills Supper Club in Southgate, Kentucky, on May 28, 1977, that claimed 165 lives.

Other fires and the count of victims have a place in history books. Within three weeks in 1980, two hotel fires gained national attention. On November 21, the MGM Grand fire in Las Vegas claimed 85 lives and on December 4 a fire in the Stouffer Inn near New York City killed 26 people. Both impacted building codes and sprinkler codes. Although it did not have the greatest toll for school fires, the fire at Our Lady of Angels Grade School in Chicago on December 1, 1958, had a lasting effect on codes and standards. Although it

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occurred nearly a century ago, the greatest human tragedy in an industrial fire occurred in New York City on March 25, 1911, at the Triangle Shirtwaist Factory. That fire took 145 lives and influenced building design standards.[1] Clearly, the attack on the World Trade Center on September 11, 2001, and the resulting fire and building collapse of the two towers holds the record for fatalities in a fire-related disaster.

Causes of Fires

In civilian fires with fatalities, the leading causes of ignition are cigarettes (35%), heating and cooking equipment (7%), matches, lighters, and candles (5%), and car crashes (4%). Leading causes of industrial fires are listed in Table 16-1.

Arson

Estimates of direct losses resulting from arson and incendiary fires in the United States range as high as $1 to $3 billion each year. The reasons for arson vary from financial problems that might be resolved through an insurance claim, to anger with an employer, school, or other person, to vandalism and other problems. Prevention of incendiary fires will not be discussed specifically in this chapter. There has been much research and study of arson cases, and most insurance companies apply specific actions that can reduce arson opportunities and potential losses. Application of fire protection designs and systems will help reduce losses for all fires.

Improving Fire Prevention and Protection

The Great Chicago Fire of 1871, many fires before it, and many since have stimulated research and action. As a result, we have the capability to prevent many fires today and to minimize the loss and damage. However, the knowledge, laws, and standards that could be used often are not applied or are ignored. Decision makers sometimes cut initial costs in hopes that fire will not strike in the future. Like other standards, fire codes are minimums, and in many cases, they can be exceeded.

TABLE 16-1 Leading Causes of Industrial Fires[a]

Percent of Fires	Causes
23	Electrical (wiring and motors, poor maintenance of equipment)
18	Smoking materials
10	Friction (bearings, jammed machines, etc.)
8	Overheated materials
7	Hot surfaces (heat from boilers, furnaces, ducts, lamps, etc.)
7	Burner flames (open flame equipment)
3–5	Combustion sparks
3–5	Spontaneous ignition
3–5	Cutting and welding
3–5	Fire from nearby facility
3–5	Arson
1–2	Sparks
1–2	Chemical action
1–2	Lightning
1–2	Molten substances

[a] Based on a Factory Mutual Engineering Corporation study of 25,000 fires over 10 years.

Outbreaks of fire were an everyday occurrence in Rome that led to the first known fire fighting organization, the Corps of Vigiles. Devastating fires in early European cities led to equipment improvements. The introduction of fire engines and pumpers in the sixteenth century began to replace bucket brigades. In 1678, Boston created the first paid fire department in the United States. Public water systems in cities emerged to provide an adequate water supply, including that needed for fire fighting. The early building codes of the seventeenth century that ensured there would be an adequate supply of ladders and buckets grew in complexity in the nineteenth and twentieth centuries. Later codes covered building design to control fire spread, water supply, and adequate means for exiting. Spurred by disasters like the Great Chicago Fire, zoning ordinances began to limit the amount of land that could be occupied by buildings to help prevent fire jumping from one property to the next. Zoning ordinances also set standards for adequate access routes for fire equipment.

Fire Codes and Standards

In the United States today, there are many fire codes. Most cities have their own, often incorporated into building codes, zoning, and other ordinances. Most states have similar codes that apply when local governments have not adopted their own standards. Most local governments adopt codes developed and maintained by standards organizations. There are several model building codes in the United States that incorporate many design requirements to minimize the chances of fire in a building, to minimize the rate at which fires spread, and to ensure exiting by occupants. Two examples are the Uniform Building Code and the code of the Building Officials Conference of America.

The National Fire Protection Association publishes and maintains a wide range of standards for many aspects of fire prevention, protection, engineering, and extinguishment, including standards for design of buildings and other facilities. This collection of standards is called the National Fire Code. Each element of this collection has an identifying number. For example, NFPA 101 is the *Life Safety Code*, which addresses safety of occupants and safe egress. There is a separate committee for each of the many codes, and each committee continually reviews and updates the code's provisions. The National Fire Code is the primary source of standards in the United States regarding matters associated with fire. Other standards include model building codes and local codes.

16-2 PHYSICS AND CHEMISTRY Of FIRE

Combustion

Fire is defined as the rapid oxidation of material during which heat and light are emitted. Combustion is an exothermic (gives off heat), self-sustaining reaction involving a solid fuel, a gaseous fuel, or both. (A fuel is any combustible material.) Most often, the reaction is oxidation of a fuel by oxygen in air. Combustion usually involves the emission of light: solid fuels usually appear to glow or smolder; gaseous fuels usually emit a visible flame.

Ignition

Ignition is the initiation of combustion. Each material has some minimum temperature, called the ignition temperature, that must be reached for ignition to occur. When some external source, such as a flame, spark, ember, or heat, causes ignition, the process is called piloted ignition. When there is no external source, the process is called autoignition, spontaneous ignition, or spontaneous combustion. The piloted ignition temperature of a fuel is lower than the autoignition temperature.

Spontaneous combustion or autoignition is often caused by heat buildup resulting from the oxidation of organic material. Bacteria and decomposition can contribute to the process in some materials. The material must reach the autoignition temperature and have enough oxygen for combustion. Among other materials, those made from agricultural products that have a high vegetable oil content, in general, are susceptible to autoignition. When left on open piles, oily rags from furniture finishing and other activities have led to many fires.

Fire Triangle and Pyramid

The components necessary for fire or combustion are (1) a fuel, (2) a source of oxygen, and (3) a source of heat or flame or some minimum temperature. As soon as combustion starts and there are sufficient amounts of the three components, combustion will continue. These three components form the fire triangle, which is illustrated in Figure 16-1(a). Technically, this model is correct for glowing combustion at the surface of solid fuels. Sources of oxygen are air, compressed air, liquid or solid oxygen, and other chemicals. There are many kinds of fuels. Paper, wood, and cloth are examples of ordinary combustibles, and there are also flammable liquid and gaseous fuels. Fuels can even be solids, like metals. Examples of heat sources are sparks, arcs, hot surfaces, and open flames.

During the process of combustion of vapors and gases in which there is a visible flame, a better model is the fire pyramid (see Figure 16-1(b)). In addition to the three components in the fire triangle, a fourth is production of hydroxyl (OH) radicals. An uninhibited reaction breaks down molecules into hydroxyl radicals, which last for an extremely short time, on the order of 1 ms.

Heat and Heat Sources

The temperature necessary to sustain combustion varies for different materials. Combustion of ordinary hydrocarbons occurs at temperatures of approximately 3,000°F, whereas some metals burn at temperatures of 5,000°F or higher. In the exothermic process of combustion, the heat given off is dependent on the fuel. Each kind of fuel has an energy or heat value per unit weight that is called heat of combustion. For example, carbon monox-

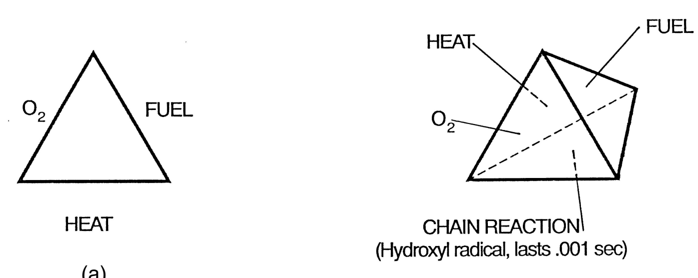


Figure 16-1. (a) The fire triangle and (b) the fire pyramid help in remembering the components involved in combustion.

ide contains 4,300 BTU/lb, paper has roughly 8,000 BTU/lb, gasoline has roughly 19,000 BTU/lb, and hydrogen has more than 51,000 BTU/lb.

The rate of heat produced during combustion is a function of the rate of combustion. Data on combustion often are available for common fuels being burned in air. When high-pressure air or gases with oxygen content more than the normal 21% (160 mmHg partial pressure) found in air are applied to combustion, the rate of heat production will increase significantly. In addition, the ignition temperature may be lowered. Limited data are available on enriched combustion.

If there is not enough oxygen available, some fuels will not burn completely. Not only will the rate of combustion slow, but partially burned fuel will become airborne. A very common product of combustion that could oxidize further is carbon monoxide. Much of the content of smoke is unburned or incompletely burned fuel. If a new source of oxygen reaches the fire, the rate of combustion can increase rapidly. For example, someone may open a window or door or a fire may break through a wall or ceiling and allow air to rush in. A flame front may actually travel very quickly along the new mixture of airborne fuel and air. In fact, the flame front may move faster than a person can run. In building fires, the sudden combustion of smoky air when a window or door is opened is called a back flash.

The rate of heat production and the location of combustion changes constantly during a fire. The total heat produced during a fire is the product of the weight of fuel consumed and the heat of combustion for the fuel. For example, if 20 lb of gasoline (a little more than 2 gal) were consumed in a fire, the total heat produced would be 20 lb $\times$ 19,000 BTU/lb = 380,000 BTU. Approximately 50 lb of paper would produce the same amount of heat, but the gasoline would burn much more quickly.

The heat from a fire is transferred to the surroundings by convection, radiation, and conduction. For most fires, heat is lost to surrounding air by convection. Because of large temperature differences between the combustion process and the air entrained into the process, tremendous upward air currents can occur. The upward movement of hot gases is driven by the thermal gradient.

Much heat is also lost through radiation. Radiation is highly dependent on geometry. One body must "see" the other for radiation heat transfer to occur. We do not feel the heat of the sun's rays when we stand in the shade because the tree prevents our body from "seeing" the sun. The surfaces surrounding a fire in a room "see" the fire and absorb much of the heat, and as the heat is absorbed by the surfaces, the room surface temperatures go up. The surfaces of a building near a fire can ignite if their temperature rises enough from the heat absorbed through radiative transfer. The rate of radiative heat transfer is a function of the fourth power of the absolute temperatures of the surfaces involved.

Methods for Controlling Combustion and Extinguishing Fires

The theory for fire found in the fire triangle and fire pyramid gives us insights into methods for extinguishing fire and stopping combustion. The fire triangle gives us three approaches: cool the fire, limit the oxygen supply, and remove the fuel. Cooling the fire reduces the temperature of the process or reduces the flame or heat source. Shutting off air supplies to a fire can stop the combustion by limiting the oxygen supply. Sometimes one can shut off the fuel by closing a valve or letting the fuel be consumed so there is none to burn. In oil fires, an explosion can sometimes separate the flame from the fuel to stop the fire. The fire pyramid yields a fourth approach: inhibiting the reaction producing hydroxyl radicals.

Products of Combustion and Their Hazards

Depending on the fuel, availability of oxygen and other factors, there can be a wide variety of products produced from combustion. Not only does combustion produce flames, heat, and smoke, but also many kinds of gases. Smoke is technically very fine solid particles suspended in air, and it may include droplets of steam. Two of the most common gases of combustion are carbon monoxide, which forms when there is not enough oxygen for complete combustion of the fuel, and carbon dioxide, which forms when combustion is complete. Other gases formed can include hydrogen sulfide, sulfur dioxide, ammonia, hydrogen cyanide, hydrogen chloride, nitrogen dioxide, acrolein, and phosgene.

Carbon monoxide is a major cause of death in fires because, first, it is a very common product of combustion and, second, relatively low concentrations can be lethal. A concentration of 1.0% or higher can cause death in 1 min or less. Carbon monoxide attaches easily to the hemoglobin of the blood's red cells, the cells that normally transport oxygen. It does not release easily from the hemoglobin, and in fact, significant levels of carbon monoxide are commonly found in fire fighters several days after a fire. As a result, at high carbon monoxide levels the oxygen supply to tissues of the body quickly deteriorates.

Carbon dioxide can contribute to fire-related deaths. At low concentrations it is not harmful. It is a normal product of combustion in cell metabolism of the body. A physiological response to increasing carbon dioxide in the blood is increased respiration rate. When one exercises, the increase in carbon dioxide signals the body that more oxygen is needed for the exercising muscles. Externally supplied carbon dioxide produces the same effect. However in a fire, increased inhalation of other combustion products creates greater danger for a person.

Lack of oxygen is another hazard in fires. A fire, particularly one in a confined space, may consume much of the oxygen available. As the normal 21% oxygen content declines, the capability of the hemoglobin of the red cells to transport oxygen to body tissues decreases. Reduced oxygen supply can impair tissue function, and when muscles are affected, motor performance goes down; when nerve cells are affected, motor performance can be impaired further and mental processes reduced. If oxygen supply is reduced enough, unconsciousness results.

Other combustion gases can have a variety of effects. The most important factors are the toxicity of each material and the level of concentration. Some materials, like hydrogen cyanide, are highly toxic and can cause death when inhaled. Acrolein, for example, is a strong respiratory irritant and can cause death in small concentrations. Ammonia is an irritant to the eyes and nose, both of which can contribute to breathing difficulties.

16-3 BEHAVIOR OF FIRE

General Movement of Hot Gases and Smoke

During a fire, the hot gases and smoke rise above the flame because of their lower density. The presence of smoke has no significant effect on the movement of the gases emanating from a fire. If the gases reach an obstruction, they move laterally until either they find an opportunity to continue a vertical movement or until they cool sufficiently to move downward.

Because of their increase in temperature, gases in a fire expand in volume. As the gases cool, they return to their original volume or near it. Combustion can create small overpressures in a closed space, and the amount of overpressure can affect movement of gases into or out of the space.

Horizontal Movement

In a closed space, the hot gases rise until they reach a ceiling, where they form a layer floating above the cooler air. There is limited direct mixing between them. The hot gases will move horizontally along the ceiling very quickly. As soon as the hot layer is confined, it increases in thickness, pushing into the cool layer below. Figure 16-2 illustrates this concept. The mass of hot gas, M, entering the upper layer is related to the size of the fire:

$$M = \frac{ph^{3/2}}{40}, \qquad (16\text{-}1)$$

where

M is in pounds per second,

p is the perimeter of the fire area in feet, and

h is the distance from the floor to the base of the hot layer in feet.

Equation 16-1 assumes that the fire is large enough for flames to reach the hot gas layer.

In 1953, a fire at a General Motors plant in Livonia, Michigan, demonstrated the disastrous effects of rapid horizontal movement of hot gases. The fire destroyed the 34-acre plant, which was under one relatively flat roof. Studies after that fire resulted in methods for limiting horizontal movement of heat and smoke.

Vertical Movement

Hot, expanded gases from a fire move vertically. In tall buildings, the movement of heat and smoke can be important. Several factors affect the vertical movement: tightness of construction, external winds, the difference between internal and external temperature, and the presence of vertical openings, such as stairways, elevator shafts, or ventilation shafts. A major factor is the stack effect, named after the movement of heat and smoke up a chimney or smoke stack.

Consider a tall narrow container. If the temperature inside the container is warmer than the temperature of air outside of it, a column of air outside will weigh more than one inside. The pressure at the bottom of the column inside the container will be less than that for the column outside the container. If the container has an opening at the bottom and at the top, the pressure outside the container will want to push air in at the bottom, and because the air inside is warmer and less dense, it will want to flow out at the top. This is called the stack effect. There are pressure differences between the two adjacent columns

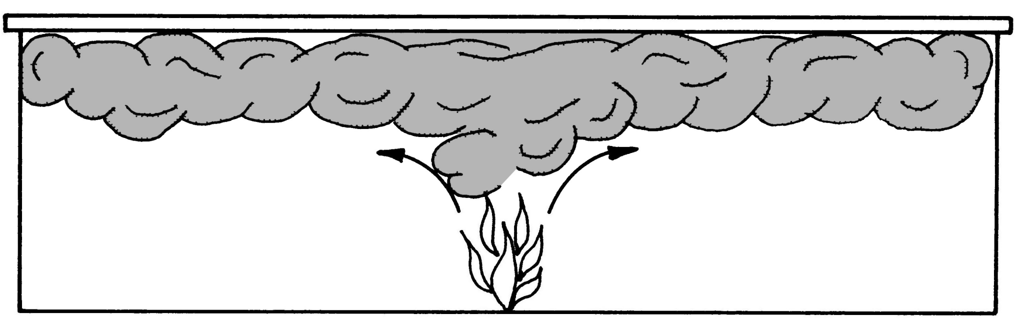


Figure 16-2. Hot gases build up and move laterally in horizontal buildings.

of air. The pressure difference, P_d, between the bottom of the container and the top defines the draft created:

$$P_d = 7.63H\left(\frac{1}{T_o} - \frac{1}{T_i}\right), \tag{16-2}$$

where

P_d is inches of water,

H is the vertical distance between inlet and outlet in feet,

T_o is the absolute temperature of the external air in degrees Rankine, and

T_i is the absolute temperature of the internal air in degrees Rankine.

Equation 16-2 assumes standard pressure and air density.

If $T_o < T_i$, air will flow into the lower opening and out the top; if $T_o > T_i$, the air will flow into the top opening and out the bottom; if $T_o = T_i$, there is no air flow.

When there is a difference between inside and outside temperatures, there is some point between the top and bottom openings where the internal and external pressures are equal. This is referred to as the neutral pressure plane. An overpressure from a fire inside a building will move the neutral pressure plane downward. If the temperature outside a building is less than that inside, a vent opening can move the neutral pressure plane upward.

The location of the neutral pressure plane can influence the distribution and buildup of smoke in a tall building. However, the movement of heat and smoke in tall buildings is not fully understood and is difficult to model. If air enters at the bottom near a fire, the fire can become more intense, adding smoke. External winds can change patterns of movement. On a hot summer day when the external air temperature is higher than the air-conditioned interior, the stack affect is reduced or eliminated.

Smoke Produced

The amount of smoke produced in a fire is difficult to predict. Studies have shown that the rate of smoke produced is related to the perimeter of the fire and the height of a clear zone of air above the fire (see Figure 16-3). During a fire, the amount of smoke produced diminishes as the layer of clear air becomes smaller. By reducing the size of a fire, the amount of smoke produced decreases.

16-4 FIRE HAZARDS OF MATERIALS

Flammable and Combustible Liquids

Classification Many of the common fuels, such as gasoline, diesel fuel, and heating oil, are liquid. Interest in the properties of these fuels resulted in a classification system and formulation of properties of liquid fuels.

NFPA developed a classification system for flammable liquids and combustible liquids (see Table 16-2) that uses flash point, vapor pressure, and anticipated ambient temperature conditions. The flash point of a liquid is the lowest temperature at which the vapor pressure of the liquid is just sufficient to produce a flammable mixture at the lower limit of flammability. Flash points are affected somewhat by laboratory test methods and other factors. The flash point is the lowest temperature of a liquid in an open container at which vapors evolve fast enough to support continuous combustion.

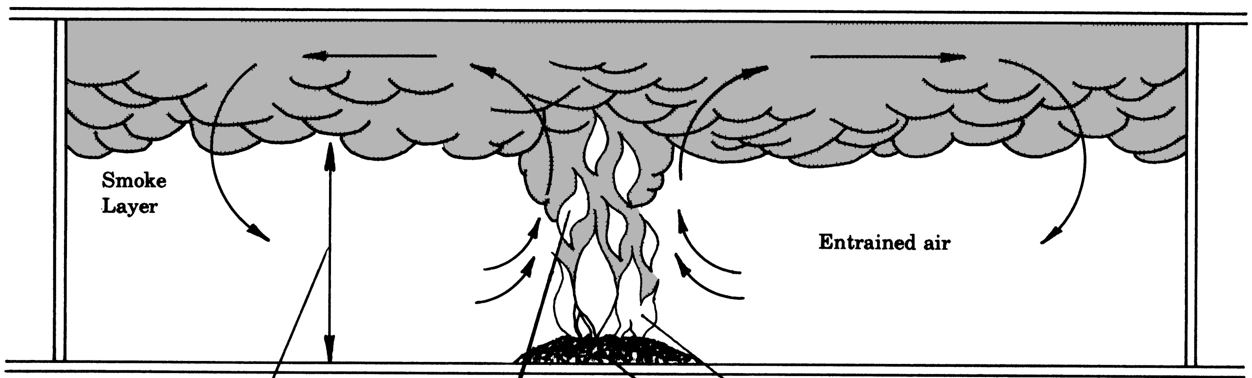


Figure 16-3. The rate of smoke production is a function of the fire perimeter and clear zone height.

TABLE 16-2 NFPA Classification for Flammable and Combustible Liquids

Category	Description
Flammable liquid	Flash point <100°F; vapor pressure <40 lb/in^2 at 100°F
Class IA	Flash point <73°F; boiling point <100°F
Class IB	Flash point <73°F; boiling point ≥100°F
Class IC	Flash point ≥73°F and <100°F
Combustible liquid	Flash point ≥100°F
Class II	Flash point ≥100°F and <140°F
Class IIIA	Flash point ≥140°F and <200°F
Class IIIB	Flash point ≥200°F

Vapor pressure is a property of a liquid in a closed container. The atmosphere above the liquid is a mixture of air and vapors of the liquid. The portion of vapor that will form in this mixture is a function of the vapor pressure of the liquid. The boiling point is the temperature at which the equilibrium vapor pressure of a liquid equals the total pressure on the surface. More simply, it is the temperature at which a liquid boils under some surrounding total pressure. Tables give vapor pressures of liquids at particular temperatures and normal boiling points (1 atm) of liquids.

In most locations, an indoor temperature could reach 100°F at some time, moderate heating is necessary to produce higher temperatures to an arbitrary limit of 140°F, and considerable heating is necessary to produce ambient temperatures higher than 140°F. These factors form the basis for the classes of flammable and combustible liquids in Table 16-2.

Vapor Volume It is known that oxygen, most commonly in air, must be present with a fuel for combustion. If there is too much or too little fuel in the mixture of fuel and air, combustion will not occur. Normally, flammable and combustible liquids themselves will not burn—the liquid fuel must vaporize.

Vapor volume is the volume of gas formed when a liquid fuel evaporates. The vapor volume can be computed from other properties of the liquid and vapor:

$$V_v = \frac{8.33 \times \text{specific gravity of the liquid}}{0.075 \times \text{vapor density of the vapor}} \tag{16-3a}$$

$$= \frac{111 \times \text{specific gravity}}{\text{vapor density}}, \tag{16-3b}$$

where

V_v is in cubic feet per gallon,

8.33 is the weight (pounds) of 1 gal of standard water, and

0.075 is the weight (pounds) of 1 ft^3 of air at standard temperature and pressure.

Some tables listing properties of flammable and combustible liquids give vapor volume directly.

Flammable Limits The mixture of fuel and standard air necessary for combustion of fuel vapors must be within certain limits. The lower flammable limit (LFL) is the minimum concentration of vapor-to-air below which propagation of a flame will not occur in the presence of an ignition source. The upper flammable limit (UFL) is the maximum vapor-to-air mixture above which propagation will not occur. Mixtures below the lower flammable limit are said to be too lean; those above the upper flammable limit too rich. The term *lower explosive limit* is equivalent to LFL, and the term *upper explosive limit* is equivalent to UFL. Flammable limits vary somewhat with temperature and pressure. The flammable range is the mixture of fuel and air between LFL and UFL. Table 16-3 gives LFL and UFL along with other properties of some flammable and combustible liquids.

Examples It is often necessary to estimate whether evaporating fuel will form a combustible mixture. Such mixtures may result from a spill in a closed space or loss of flammable material in a process. An exact determination is not always possible, because vapors may not mix uniformly throughout the space. Vapors from a solvent tank may be heavier than air, may evaporate at the surface of the liquid, may slide over the edge of the tank, and may concentrate near the floor. In another case, vapors may be lighter than air and may concentrate near a ceiling. For some computations of this type, it is useful to apply an adjustment factor for incomplete mixing and local concentrations.

Example 16-1 Consider the case of a child who used gasoline to clean his hands in a bathroom. There was a gas water heater in the same room. While cleaning his hands, the gasoline vapor ignited and the child was severely burned. Assume the room was $6 \times 10 \times 8$ ft.

(**a**) Assuming full mixing (uniform vapor–air mixture throughout the room), how much gasoline had to evaporate to reach a combustible mixture?

(**b**) Assume there was incomplete mixing (nonuniform vapor–air concentrations in the room). Apply an adjustment factor of 5 and estimate the minimal amount of vapor required to develop a locally combustible mixture in the room.

(**c**) Will the vapors of gasoline concentrate at the floor or at the ceiling when evaporating in air?

The room volume is 480 ft^3. From Table 16-3, the LFL for gasoline is assumed to be 1.4% in air. The vapor volume of gasoline necessary for combustion is then $480 \times 0.014 = 6.72\,ft^3$. From Table 16-3, the vapor equivalent of gasoline is assumed to be 24 ft^3/gal. Thus, the minimum volume of liquid gasoline that must evaporate to produce the LFL is 6.72/24 = 0.28 gal. For unequal mixing, the estimated minimum is 0.28/5 = 0.056 gal, assuming a factor of 5 is a reasonable adjustment factor. This is approximately 14 tablespoons of gasoline. From Table 16-3, the vapor density of gasoline is 3 to 4. Because the vapors are much denser than air, they will concentrate quickly at the floor, where the source of ignition for a gas water heater is located and a combustible mixture will form quickly.

Flammable Gases

Flammable gases refer to those gases that exist at standard temperatures and pressures (above the normal boiling point of a gas) and burn in normal concentrations of oxygen in air. Flammable gases must combine in appropriate mixtures with air for combustion to occur and they must be at or above their ignition temperature to burn. Any substance that has a vapor pressure of more than 40 lb/in^2 (absolute) at 100°F in its liquid state is considered a gas. Like vapors of flammable and combustible liquids, the specific gravity of a gas can be important when analyzing fire potential. Full mixing in a space may not occur, but local concentrations may build up and reach combustible mixtures.

TABLE 16-3 Properties of Selected Flammable Liquids[a]

Liquid	Flash Point °F	Boiling Point °F	Ignition Temp. °F	Flammable Limits Vol. % LFL	UFL	Specific Gravity (Water = 1)	Vapor Density (Air = 1)	Vapor Volume (ft^3/gal)
Acetaldehyde	–38	70	347	4.0	60	0.8	1.5	58
Acetone	–4	133	869	2.5	13	0.9	2.0	44
Acrolein	–15	125	428	2.8	31	0.8	1.9	—
Allylamine	–20	128	705	2.2	22	0.9	2.0	—
Amyl acetate	60	300	680	1.1	7.5	0.9	4.5	22
Benzol (benzene)	12	176	928	1.3	7.9	0.9	2.8	37
Butadiene monoxide	<–58	151	—	—	—	0.9	2.4	—
Butyl alcohol	98	243	650	1.4	11.2	0.8	2.6	—
Butyl chloride	15	170	860	1.8	10.1	0.9	3.2	—
Carbon disulfide	–22	115	194	1.3	50	1.3	2.6	54
Cyclohexane	–4	179	473	1.3	8	0.8	2.9	30
Denatured alcohol	60	175	750	—	—	0.8	1.6	—
Dibutyl ether	77	286	382	1.5	7.6	0.8	4.5	—
Dichloroethylene-1,2	36	119	860	5.6	12.8	1.3	3.4	43
Diethylamine	–9	134	594	1.8	10.1	0.7	2.5	32
2,2-Dimethylbutane	–54	122	761	1.2	7.0	0.6	3.0	—
2,3-Dimethylpentane	<20	194	635	1.1	6.7	0.7	3.5	—
P-diokane	54	214	356	2.0	22	1.0+	3.0	39
Divinyl ether	<–22	102	680	1.7	27	0.8	2.4	—
Ethyl acetate	24	171	800	2.0	11.5	0.9	3.0	33
Ethyl alcohol	55	173	685	3.3	19	0.8	1.6	56

Ethylamine	<0	62	725	3.5	14	0.8	1.6	50
Ethyl chloride	–58	54	966	3.8	15.4	0.9	2.2	46
Ethyl ether	–49	95	356	1.9	36	0.7	2.6	31
Gasoline	–45	100–400	536–853	1.4	7.6	0.8	3–4	24–32
Hexadiene-1,4	–6	151	—	2.0	6.1	0.7	2.8	—
Hexane	–7	156	437	1.1	7.5	0.7	3.0	25
Isopropyl alcohol	53	181	750	2.0	12.7	0.8	2.1	—
Jet fuel (JP-4)	−10–+30	—	464	1.3	8.0	—	—	—
Kerosene	100–162	304–574	410	0.7	5	<1	—	—
Methyl alcohol	52	147	867	6.07	36	0.8	1.1	80
Methylcyclohexane	25	214	482	1.2	6.7	0.8	3.4	26
Methyl ethyl ether	–35	51	374	2.0	10.1	0.7	2.1	—
Methylethylketone	16	176	759	1.4	11.4	0.8	2.5	36
Naphtha V.M. & P.	28	212–320	450	0.9	6.0	<1	—	—
Nitroethane	82	237	778	3.4	—	1.1	2.6	46
Paraldehyde	96	255	460	1.3	—	1.0–	4.5	—
Pentane	<–40	97	500	1.5	7.8	0.6	2.5	29
Petroleum ether	<0	95–140	550	1.1	59	0.6	2.5	—
Propanol	–22	120	405	2.6	17	0.8	2.0	—
Propylene oxide	–35	94	840	2.3	36	0.8	2.0	—
Toluol	90	231	896	1.2	7.1	0.9	3.1	—
Turpentine	95	300	488	0.8	—	<1	1.8	—
Vinyl ethyl ether	<–50	96	395	1.7	28	0.8	2.5	—
Xylene-o	90	292	867	1.0	7.0	0.9	3.7	27

[a] Most properties from NFPA 325M.

Nonflammable gases are those that do not burn in any concentration of air or oxygen. Inert gases are those that will not support combustion. Some gases, called reactive gases, will react with other materials in processes other than combustion. An example is chlorine reacting with hydrogen. Chlorine is a nonflammable (but toxic) gas and hydrogen is a flammable gas, and although their reaction will produce a flame, the reaction does not involve oxygen. Besides being combustible or reactive, gas toxicity is another hazardous property (see Chapter 24). Another hazard of gases is related to the Boyle-Charles law (see Chapter 19). Gases are classified in other ways, based on physical properties and use.

Other Materials

Besides flammable and combustible liquids and flammable gases, there are many other kinds of materials that will burn. Some of the major ones are wood, metals, and plastics.

Wood Wood and wood products, like pulp, paper, and cardboard, will burn. There is considerable variation in the heat value of different wood species and products. During combustion, wood will char, that is, form a layer of partially burned material (similar to charcoal) that insulates material below it from the heat of combustion and slows the burning rate. In fact, wood can retain many of its structural properties in a fire for some time because of, to a large extent, the insulating effect of the char formation.

People have studied the ignition and charring of wood. Ignition temperatures vary significantly, depending on the moisture content, density, and other factors. When wood burns, moisture and other noncombustible gases are driven from it initially. As combustion progresses, the temperature increases and water vapor and carbon monoxide are produced. Until this point, wood has absorbed heat, but the wood reaches higher temperatures, flammable vapors and particulates form an exothermic reaction, and charcoal is formed. In general, the ignition temperature of wood declines as combustion moves through the preceding stages. Ignition temperatures for test blocks are on the order of 300° to 400°F. Charcoal may ignite at significantly lower temperatures.

Metals Most metals burn under certain conditions. Small cross sections and fine particles burn more readily than thick solids. Some metals are called combustible because they are relatively easy to ignite. Combustible metals include magnesium, titanium, zinc, sodium, lithium, some radioactive metals, and others. Burning metals create special extinguishment problems. For example, dumping water on a titanium fire may add to the fire. The water may break down into oxygen and hydrogen and the oxygen combining with titanium and hydrogen becomes another fuel. Magnesium burns in a carbon dioxide atmosphere. Aluminum, iron, and steel do not burn easily because they do not react with oxygen easily. Fine metal powders may ignite easily and explode like other dusts (see Chapter 17).

Plastics There is a wide variety of plastics, some with special additives to achieve particular properties. They vary in many ways, including fire-related properties. However, some generalizations illustrate their hazards. Plastics tend to have higher ignition temperatures than wood. Some have a rapid flame spread rate and some are easily ignited and burn rapidly. Many plastics produce dense, black smoke during combustion, often because of the additives that inhibit flammability. Like other materials, most plastics produce carbon monoxide and many also produce other toxic gases. During combustion, plastics tend to melt, which may result in drippings that spread the fire. Cellular plastics without flame retardants tend to create fast-spreading, high-intensity, dense smoke fires.

Identification of Hazards of Materials

NFPA developed a system for identifying fire hazards of materials that has been in use for some time.[2] The system presents information on labels and placards about three types of hazards, which are subdivided into five levels of severity. The information is useful for fire fighters and others and is presented in a four-quadrant diamond symbol. As illustrated in Figure 16-4, three quadrants are for the three kinds of hazards: health, flammability, and reactivity. The lower quadrant contains special information and symbols. One symbol, a W with a horizontal line through it, shows that a material has a hazardous reaction with water. Another symbol is the radioactive pinwheel symbol (see Figure 22-2). Numbers in each quadrant give the degree of the hazard. General interpretations for degree of hazard are as follows:

0. No special hazards, therefore no special measures for fire fighting.

1. Nuisance hazards are present that require some care; standard fire fighting procedures can be used.

2. Hazards are present that require certain equipment or procedures to handle these materials safely; can be fought with standard procedures.

3. Fire can be fought using methods intended for extremely hazardous situations, such as unmanned monitors or personal protective equipment that prevents all bodily contact.

4. Too dangerous to approach with standard fire-fighting equipment and procedures; withdraw and obtain expert advice on how to handle.

Degree of hazard information is included in Figure 16-4. Further data and interpretations for specific types of hazards are found in NFPA 704.

16-5 FIRE SAFETY IN BUILDINGS

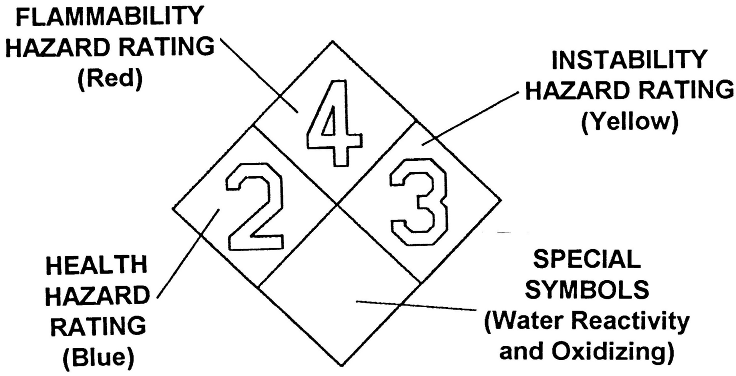
Fundamentals

There are at least two important lessons learned from the Great Chicago Fire of 1871. One resulted from the inability of fire equipment to move down congested streets to a location where they could fight parts of the fire effectively and the other resulted from the rate at which the fire spread. The density of frame structures on lots was a big factor. Fed by the wind, fire leaped from building to building very quickly. Undoubtedly, radiation, convection, and wind-blown sparks all played a large part in the process. As a result, rules were written for layout of communities, streets, building sites, water supplies, and construction of buildings. Other fires added to these lessons and influenced today's standards as well.

The main objectives for fire safety in buildings are (1) getting occupants out safely, (2) minimizing property loss for structures and contents, and (3) minimizing interruption of operations. Through continued study, knowledge of fire behavior and building design makes it possible to minimize fire losses. Often the goal is to confine a fire to the site of origin, then to the building of origin. Through proper design of facilities, one can confine most fires to the floor and even the room of origin.

Site Planning and Accessibility

Fire departments and equipment should have access to all sides of a building. Access roads should be adequate even during peak traffic loads. Landscaping, external structures, and



DEGREE OF HAZARD	HEALTH HAZARD RATING	FLAMMABILITY HAZARD RATING	INSTABILITY HAZARD RATING
4	Materials that, under emergency conditions, can be lethal.	Materials that will rapidly or completely vaporize at atmospheric pressure and normal ambient temperature or that are readily dispersed in air and will burn readily.	Materials that in themselves are readily capable of detonation or explosive decomposition or explosive reaction at normal temperatures and pressures.
3	Materials that, under emergency conditions, can cause serious or permanent injury.	Liquids and solids that can be ignited under almost all ambient temperature conditions. Materials in this degree produce hazardous atmospheres with air under almost all ambient temperatures or, though unaffected by ambient temperatures, are readily ignited under almost all conditions.	Materials that in themselves are capable of detonation or explosive decomposition or explosive reaction, but that require a strong initiating source or that must be heated under confinement before initiation.
2	Materials that, under emergency conditions, can cause temporary incapacitation or residual injury.	Materials that must be moderately heated or exposed to relatively high ambient temperatures before ignition can occur. Materials in this degree would not under normal conditions form hazardous atmospheres with air, but under high ambient temperatures or under moderate heating could release vapor in sufficient quantities to produce hazardous atmospheres with air.	Materials that readily undergo violent chemical change at elevated temperatures and pressures.
1	Materials that, under emergency conditions, can cause significant irritation.	Materials that must be preheated before ignition can occur. Materials in this degree require considerable preheating, under all ambient temperature conditions, before ignition and combustion can occur.	Materials that in themselves are normally stable, but that can become unstable at elevated temperatures and pressures.
0	Materials that, under emergency conditions, would offer no hazard beyond that of ordinary combustible materials.	Materials that will not burn under typical fire conditions, including intrinsically noncombustible materials such as concrete, stone, and sand.	Materials that in themselves are normally stable, even under fire conditions.

Figure 16-4. NFPA symbol system for identification of hazards of materials. (Refer to NFPA 704.)

vehicle parking should not create barriers to access. Water supplies, hydrants, and valves should be located conveniently to support fire-fighting strategies. Adequate pressures and quantities of water must be available. If special hazards exist and other kinds of extinguishing agents are needed, they must be planned into the site in adequate amounts and at effective locations. Gas lines and supply lines for other fuels entering a facility should have shutoff valves located where it is not dangerous to operate them in a fire. An example is a vehicle driving away from a gas pump, catching a fuel hose, and starting a fire. If the shutoff is at the pump, it would be difficult to approach and shut off the fuel.

Separation of Structures

Buildings should have sufficient separation to minimize fire traveling from one building to another. Distance between buildings is one way to provide separation. Shielding by fire walls is another way. Other design features, such as parapets, minimal wall openings to adjacent buildings, fire resistant door and window materials for openings, automatically closed doors, dampers, and shutters, all will help limit fire movement between buildings. So will sprinkler systems and water curtains. Many factors affect design decisions made to meet separation requirements. Type of construction, building height, size of exposed walls, and amount of openings in building walls are a few considerations.

Building Construction

A designer has a wide choice of materials and methods of assembly for a building design. The materials and the methods of assembly can affect the ability of a building to meet fire safety objectives and also can affect insurance premium rates.

Fire Resistance Ratings Fire resistance is a rating for building assemblies and components based on laboratory tests. Given in units of minutes or hours, the fire resistance ratings indicate how long an assembly or component will withstand a particular test fire. The objective is to confine a fire long enough and to ensure that a structure will not collapse to allow occupants to escape and fire fighting to begin containment and extinguishing tasks.

Building Construction Classification There are many ways to classify the materials and methods of assembly used in a building. The current NFPA classification scheme considers the ability to retain structural integrity and to provide fire barriers and to recognize the fuel contribution of the structure and the enclosing walls and roof. Classifications consider other features to limit fire and smoke movement and to meet other fire safety requirements within the building. The classifications and a brief description of each are found in Table 16-4.

Structural Integrity

Many factors affect the ability of a building and the assemblies of materials in it to continue to carry loads during a fire. Designers use analytical design, data from design tables and guides, codes requirements, and tests results to reach decisions.

Materials expand when heated and contract when cooled, and different materials have different coefficients of thermal expansion. If expansion during a fire is not incorporated into a design, structural damage may result from excessive loads that members place on each other, often related to buckling and other failures not created by direct heat damage to materials or by combustion.

TABLE 16-4 NFPA Classifications of Building Construction

Classification	Description
A. Type of construction (from NFPA 220)	
Fire-resistive	Structural members including walls, partitions, columns, floors, and roofs are of noncombustible or limited-combustible materials and have fire resistance ratings that meet or exceed particular fire resistance ratings.
Noncombustible/ limited-combustible	Walls, partitions, and structural members are of noncombustible or limited-combustible materials, but do not qualify as fire-resistive construction.
Protected noncombustible/ limited-combustible	Bearing walls or bearing portions of walls, exterior or interior, are of noncombustible or limited-combustible materials and have minimum hourly fire resistance ratings and stability under fire conditions, and floors and roofs and their supports have minimum hourly fire resistance ratings.
Heavy timber	Bearing walls or bearing portions of walls are of noncombustible or limited-combustible materials and have minimum hourly fire resistance ratings and stability under fire conditions; nonbearing exterior walls are of noncombustible or limited-combustible materials; columns, beams, and girders are of heavy timber, solid or laminated; and floors and roofs are of wood without concealed spaces. In addition, components and assemblies must meet certain dimensional and other criteria.
Ordinary	Exterior bearing walls or bearing portions of exterior walls are of noncombustible or limited-combustible materials and have minimum hourly fire resistance ratings and stability under fire conditions; nonbearing exterior walls are of noncombustible or limited-combustible materials; and roofs, floors, and interior framing are wholly or partly of wood of smaller dimensions than required for heavy timber construction.
Protected ordinary	Ordinary construction may be designated as "protected" when roofs and floors and their supports have minimum hourly fire resistance ratings.
Wood frame	Exterior walls, bearing walls and partitions, and roofs and their supports are wholly or partly of wood or other combustible materials, when the construction does not qualify as heavy timber construction or ordinary construction.
Protected wood frame	Wood frame construction may be designated "protected" when roof and floors and their supports have minimum hourly fire resistance ratings.
B. Class of occupancy (primary classifications from NFPA 101)	
Assembly	An occupancy used for a gathering of 50 or more persons for deliberation, worship, entertainment, eating, drinking, amusement, awaiting transportation, or similar uses or used as a special amusement building, regardless of occupant load.
Educational	All buildings used for educational purposes through the twelfth grade by six or more persons for 4 hours per day or more or more than 12 hours per week.
Health care	Used for purposes of medical or other treatment or care of four or more persons where such occupants are mostly incapable of self-preservation because of age, physical or mental disability, or because of security measures not under the occupants' control. They include hospitals, nursing homes, and limited care facilities.

TABLE 16-4 continued

Classification	Description
Detention and correctional	Used to house four or more persons under varied degrees of restraint or security where such occupants are mostly incapable of self-preservation because of security measures not under the occupants' control.
Residential	An occupancy that provides sleeping accommodations for purposes other than health care or detention and correctional. Residential occupancies are further divided into one- and two-family dwellings, lodging and rooming houses, hotels and dormitories, apartments, residential board, and care facilities.
Mercantile	Used for the display and sale of merchandise.
Business	Used for account and record keeping or the transaction of business other than mercantile.
Industrial	An occupancy in which products are manufactured or in which processing, assembling, mixing, packaging, finishing, decorating, or repair operations are conducted.
Storage	Used primarily for the storage or sheltering of goods, merchandise, products, vehicles, or animals.
C. Hazard of contents (from NFPA 101)	
Low hazard	Those of such low combustibility that no self-propagating fire therein can occur.
Ordinary hazard	Those that are likely to burn with moderate rapidity or to give off a considerable volume of smoke.
High hazard	Those that are likely to burn with extreme rapidity or from which explosions are likely.

The strength properties of many materials are affected by temperature. For example, when heated, steel quickly loses its ability to carry a load, even its own weight, if the temperature is high enough. To slow the rate of temperature rise, steel normally is covered with materials (plaster, gypsum, and other materials) that insulate it from the high gas temperatures in a fire.

Wood is a combustible material. However, depending on moisture content, it may not collapse rapidly because of the insulating effect that char provides. Some materials, like wood and other combustibles, can be treated with substances that slow the rate of burning.

Concrete is a common structural element. Although it has some insulating properties, heat can damage it, causing loss of strength, spalling, and other effects from heat. The kinds of materials in concrete and their mix affect its ability to withstand a fire. If heat reaches reinforcing materials in concrete, significant structural capacity can be lost.

Confinement

A major objective in building design is limiting a fire to the area of origin. Confining a fire to a small area is best. Some call this strategy compartmentation. A building and each portion of it are designed to restrict horizontal and vertical movement of fire, smoke, and heat. Partitioning assemblies, doors, windows, duct runs, and other openings are designed to meet fire ratings. The confinement should function until a fire is extinguished or burns itself out. When confinement is the criterion, potential fire severity determines what fire resistance is needed. As noted earlier, time to exit and time for fire fighters to begin control and extinguishing actions are also criteria for determining fire resistance.

Fire Load

A fire is characterized by three stages: growth from a small origin, full development, and decay. In a fully developed fire, the temperature in a confined space will reach 1500° to 2300°F. Before or during full fire development, the contents of a room may burst into flames. This is called flashover.

The severity of a fire in terms of intensity and duration is a function of the quantity of combustibles available, their burning rate, and the air available for combustion. The surface area of fuel and the amount of oxygen control combustion. The greatest heat load occurs when just enough ventilation is present so the rate of combustion is controlled by the fuel surface area. At low oxygen supply rates, ventilation limits the rate of combustion. At high ventilation rates, heat is removed from the area of the fire, which reduces the heat transfer rate. Plots of time and temperature provide a basis for assessing fire severity. Fires with different temperature histories are compared with standard time-temperature profiles. A test fire is equivalent in severity to the standard when the areas under the time-temperature curves are equal. Barriers, such as walls, floors, ceilings, and doors, must be able to withstand the desired fire severity.

Studies have shown a relationship between fire severity and fire load. One can determine fire load during design or use of a building and have some idea of the severity potential. Fire load is the maximum heat released if all combustibles in a fire area burn, including heat from combustible contents and combustible interior finish, floor, and structural materials. Fire load is usually expressed as equivalent combustible weight divided by the fire area and is given in pounds per square foot. Actual fire loads are adjusted to the equivalent heat of combustion of ordinary combustibles, assumed to be 8,000 BTU/lb. Table 16-5 gives approximate heat of combustion data for some common materials.

Example 16-2 Assume that a warehouse contains 1,000 lb of epoxy stored in a 50 ft^2 area. What is the fire load? The heat of combustion of epoxy is approximately 14,400 BTU/lb. The fire load is 1,000 lb × 14,400 BTU/lb/8,000 BTU/lb/50 ft^2 = 36 lb/ft^2.

When ordinary combustibles, such as paper, are stored in steel containers, they will not burn completely and will not contribute the full heat value of the materials. Usually, ordinary combustibles stored in partially and completely enclosed steel containers are derated when estimating fire loads.

For fully enclosed containers, the ratio of fully enclosed combustible weight, W_E, to the total weight of all combustibles, F_T, determines what derating factor, K, is used:

W_E/F_T	K
<0.5	0.4
0.5–0.8	0.2
>0.8	0.1

For containers that have one side open (partially enclosed), the weight of ordinary combustibles, W_P, is derated by $K = 0.75$.

The total derated fire load, F_L, is the sum of combustibles in the open, derated fully enclosed combustibles, and derated partially enclosed combustibles.

TABLE 16-5 Approximate Heat of Combustion for Some Common Materials

	Approximate Heat of Combustion	
Material	(MJ/kg)	(BTU/lb)
Charcoal	33.7–34.7	14,492–14,879
Coal		
Anthracite	30.9–34.6	13,288–14,879
Bituminous	24.7–36.3	10,621–15,610
Cotton	16.5–20.4	7,096–8,773
Gasoline	46.8	20,126
Kerosene	46.4	19,954
Leather	18.2–19.8	7,527–8,515
Oil, linseed	34.2–39.4	16,857–16,943
Paper		
Brown	16.3–17.9	7,010–7,698
Magazine	12.7	5,461
Newsprint	21.5	9,246
Rubber (auto tires)	32.6	14,019
Starch	17.6	7,569
Straw	15.6	6,708
Wheat	15	6,451
Wood		
Birch	20	8,600
Douglas fir	21	9,031
Maple	19.1	8,214
Red oak	20.2	8,687
Spruce	21.9	9,375
White pine	19.2	8,257
Hardboard	19.9	8,558
Wool	20.8–26.6	8,945–11,439

Fire Spread

The objective of compartmentation is to confine a fire to the room or area of origin. Wall, floor, ceiling, and opening barriers are rated to help achieve that goal. When rated barriers are in place, fires do not spread readily by heat transfer or structural failure of the barriers. They spread primarily through horizontal and vertical openings, such as open doors and unenclosed stairs and shafts.

Many buildings have interstitial spaces between floors for electrical and communication lines, heating and cooling ducts, and steam and water lines. Fires in these hidden areas can burn for some time. When they break through a ceiling, for example, they can spread very rapidly across an open room. A flame front often will travel faster than occupants can run.

Vertical openings may exist between wall surface materials and vertical shafts may house electrical, communication, and other building services. Laundry chutes, elevator shafts, ventilation shafts, or atriums are all examples of vertical openings.

Preventing fire spread through horizontal and vertical openings in buildings may be difficult, but a number of approaches can reduce the rate of spreading. Where possible, concealed spaces should not have combustible materials. Like other spaces, they should be enclosed with rated barriers. Fire-retardant coatings may help. Vertical openings should be blocked where possible. Fire stops refer to a wide range of methods for sealing concealed spaces, including blocking between wall studs. Fire stops also include protective devices and systems for sealing conduits, pipe and other penetrations, foam-in-place sealants, and other noncombustible materials, even sand. Fire doors and shutters are useful for larger openings for escalators and conveyors. Limiting fire spread in atriums requires a combination of design features.

16-6 INDUSTRIAL AND PROCESS FIRE HAZARDS

General

In many ways, the fire hazards in industrial facilities are the same as in other facilities. One major difference is the quantity of materials, fuels, and power present in one location. Each kind of operation and process presents particular fire prevention and protection problems. This text cannot discuss in detail each operation, process, and kind of material. A few operations, principles, and procedures give examples. One should consult specific references to find out more about particular fire hazards and controls.

Venting

One problem found across many industries and processes is the use of single-story facilities. As noted earlier, heat and smoke can move rapidly under the roof of a horizontal building. There are some techniques that can help confine fires in industrial plants. Ventilation is an important method. Roof vents allow hot gases to escape and do have some effect on confinement. Compartmentation will help limit the horizontal spread of fire. In industrial plants, full partitions may interfere with the flow of materials and production activities. Where large open spaces are needed and to avoid interfering with manufacturing and material handling processes, partial partitions may hang from the ceiling. Curtain boards are vertical panels constructed of noncombustible materials that are suspended from the ceiling. When they fit tightly to the ceiling and extended as far to the floor as possible, they can prevent the lateral movement of a hot gas layer. In effect, curtain boards can partition a large plant into smaller areas to control fire spread. Figure 16-5 illustrates the use of curtain boards.

Vents should be located within each area or section created by curtain boards. From knowledge of fire behavior and the development of a hot gas layer below a ceiling, an expression for the amount of vent area, A, required for a section is

$$A = 0.14\frac{ph^{3/2}}{d^{1/2}}, \qquad (16\text{-}4)$$

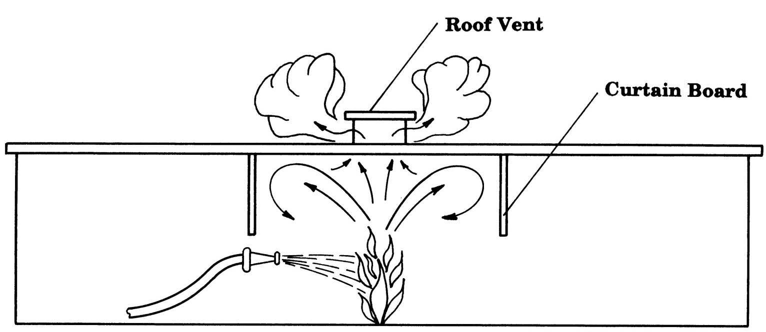


Figure 16-5. Example of curtain boards for limiting fire spread in horizontal construction.

where

A is the vent area required in square feet,

p is the perimeter of the fire area in feet,

h is the distance from the floor to the base of the hot gas layer in feet, and

d is the depth of the layer in feet.

Example 16-3 In a factory, the curtain boards hang 10 ft from the ceiling. The bottoms of the curtain boards are 14 ft from the floor. If a fire is located in a 4 ft × 5 ft area and one assumes that the hot gas layer formed along the ceiling extends half the distance to the bottom of the curtain boards, how much vent area is needed?

The perimeter of the fire is (2)(4 + 5) = 18 ft. Then, applying Equation 16-4,

$$A = \frac{0.14(18)(14+5)^{3/2}}{5^{1/2}} = 93.3\ \text{ft}^2.$$

Fire Walls

Another way to prevent lateral spread of fire in large buildings or between buildings is by using fire walls. Fire walls must withstand the potential for complete burnout on both sides. They require special structural construction so heat and collapse of other building components will not affect their stability. Fire walls often are visible from outside a building, because they have a parapet extending approximately 3 ft above the roof line. The parapet helps prevent fire from burning along the roof and across the fire wall. Fire walls have some limitations, and other partitioning methods may be substituted.

Welding and Cutting

Common industrial processes are welding and cutting. Unsafe welding and cutting procedures and equipment too often lead to fires. Heating certain materials with welding equipment may produce toxic gases and vapors. Welding processes also can damage eyes. Later chapters discuss these hazards. One should also reference special publications on welding and cutting equipment and operations that provide more details on hazards and controls.

The main types of welding are electric welding and oxygen-fuel welding. The most common form of electric welding is arc welding. An arc is made to pass between the metal to be welded and an electrode. There are several kinds of electrodes, some containing the filler material for the joint. The electric arc creates a high, localized temperature that melts the filler material and heats the surrounding metal. There are several variations to the basic arc welding process for different metals and for improved control in automated welding.

In oxygen-fuel welding a fuel (the most common fuel is acetylene, although others are sometimes used) is mixed with oxygen in a nozzle device or torch. Both oxygen and fuel move from separate compressed gas tanks through pipes and hoses to the torch. When ignited, the rate of fuel can be adjusted to achieve very high temperatures that heat the metals being joined and the filler material to form a bond.

Metals also can be cut by using the high temperatures achieved by arc and gas welding processes. A narrow band of metal is oxidized to form a cut.

Fire hazards result from the high temperature and open flame equipment, scattering of sparks and hot metal particles, the welding equipment itself, the objects being worked on and the environments. In welding and cutting operations, sparks and hot particles fly from the operation and may fall to lower locations or into cracks and openings. The sparks and hot particles can travel as far as 30 to 50 ft and are capable of igniting flammable and combustible material within such a range. Because persons performing welding wear high-density glasses or face shields, they cannot see what is going on in lower light levels. They also may not be able to monitor such a large area. When the welding operation cannot be confined or performed in a safe location free of combustibles, a fire watcher assists the welder. The fire watcher's job is to monitor the area around the operation for lingering sparks or fire and to extinguish them.

Welding equipment needs special care to ensure that it is not accidentally operated. Oxygen must be handled carefully and maintained properly. Leaking oxygen could get into clothing and other material and cause rapid flame up if ignited. Electrical equipment must be grounded, and all equipment should comply with electric codes. Cylinder valves should be closed when not in use. Leaking fuels, such as acetylene and butane, have led to many explosions related to welding and cutting.

The objects worked on and the environment must have proper controls as well. Quite often one hears of a person who attempts to repair a container that had a fuel in it. The vapors ignite and explode, usually resulting in severe injury or death. By filling such containers with water or sand or by cleaning them and flushing out residual fuel, welding can be performed safely. The environments for welding and cutting must be free of flammable gases. In confined spaces, adequate ventilation and breathing air is needed. Welders should wear proper protective clothing, and welders and others involved in welding and cutting operations must have training in the operations, their hazards, and proper controls.

Hot Work Permit Procedures

Many organizations use a permit procedure for all hot work, except that involving normal operations or processes. Hot work is any kind of welding, cutting, burning, or activity that involves or generates sparks or open flame. It includes heated equipment that may provide an ignition source for a fire. Hot work often involves people from a maintenance department going to other departments to perform activities. The main idea in a hot work permit procedure is to ensure that supervisors of all departments involved and workers who may be involved in any way in the work participate in the decision to start work and to conduct it safely. A sample hot work permit procedure is outlined in Figure 16-6.

Storage

Storage of flammables and combustibles requires special attention. A few fundamental storage principles are covered here. References and applicable sections of the National Fire Code have much more to say about particular storage matters related to fire protection.

Indoor Storage of Flammable Liquids

Flammable liquids are used in many operations for cleaning, as fuel for equipment, and for other purposes. To prevent fires, there are many requirements for storage and dispensing of flammable liquids indoors. One general principle is to limit the quantity of flammables stored in an occupied or operational area to that needed for specific jobs or a single day. Larger quantities should be stored in special facilities separate from occupied and operational areas.

PERMIT
Cutting and Welding
with Portable Gas or Arc Equipment

Date ____________________ Building ________________

Dept ____________________ Floor __________________

Work to be completed ________________________________

____

Special precautions to be taken ___________________________

____

Fire watch required? ☐ Yes ☐ No

I have examined the location where this work is to be performed, identified the necessary precautions, and therefore grant permission for this work as show on the reverse side of this permit.

Permit expires ____________

Signature ____________________________
(Person responsible for authorizing welding and cutting work.)

Time and Date: Work started ________________________

Completed __________________________

FINAL CHECK-UP

I have inspected the work area and all surrounding areas for sparks and heat (including floors above and below, opposite sides of walls, and enclosed areas) at least 30 minutes after the work was completed and found no signs of combustion.

Signed ____
(Supervisor or Fire Watcher)

Figure 16-6. An example of a hot work permit form.

Storerooms Special storerooms confine flammable liquids. NFPA has detailed design standards for these storerooms. Fire codes limit the quantities and sizes of containers that can be stored indoors. Some design features for flammable storerooms are explosion-proof switches and electrical fixtures, ventilation, self-closing doors with fusible links, a static electricity grounding system, special signage, raised door sill, and special floor contours.

Storage Cabinets Storage cabinets may be located outside special storerooms. Standards and codes specify their design and construction and limit the quantities of flammables they may contain. Cabinets help protect stored liquids from fires outside them, confine spills within them, and keep flammables organized. There are also various styles of safety cans and vertical or horizontal dispensing drums.

Grounding and Bonding When flammables are transferred from storage drums to small dispensing containers or when there are transfers of large quantities of flammables, the containers involved must be connected to each other (bonding) by an electrical con-

PROCEDURE SUMMARY

Before approving any cutting and welding permit, the fire safety supervisor or his appointed alternate shall inspect the work area and confirm that all necessary precautions have been taken to prevent fire in accordance with NFPA standards and company policy.

PRECAUTIONS

☐ Sprinklers in service
☐ Cutting and welding equipment is in good repair

WITHIN 35 FEET OF WORK

☐ Floors are swept clean of combustibles
☐ Combustible floors are wet down, covered with damp sand, metal or other shields
☐ No combustible material or flammable liquids are present
☐ Combustibles and flammable liquids are protected with covers, guards, or metal shields
☐ All wall and floor openings are covered
☐ Covers are suspended beneath work to collect sparks

WORK ON WALLS OR CEILINGS

☐ Construction is noncombustible and without combustible covering
☐ Combustibles are moved away from opposite side of wall(s)

WORK ON ENCLOSED EQUIPMENT
(Tanks, containers, ducts, dust collectors, etc.)

☐ Equipment is cleaned of all combustibles
☐ Containers are purged of flammable vapors

FIRE WATCH

☐ To be provided during and for 30 minutes after operation
☐ To be supplied with extinguisher and small hose
☐ Fire watcher is trained in use of equipment and in sounding fire alarm

FINAL CHECK-UP

☐ To be made 30 minutes after completion of any operation unless fire watch is provided

Signed ______________________________
(Supervisor)

Figure 16-6. *continued*

ductor or both must be connected to a grounding rod or line. (See Chapter 12 for a discussion of bonding and grounding.)

Drums Flammable liquids must be stored in closed containers and may be dispensed from drums by gravity or suction pump, not by pressurizing the drum. Valves for gravity dispensing must be approved by a recognized testing laboratory and must close automatically. Drip containers are required for catching leaked fluids.

Safety Cans Safety cans contain 5 gal or less of flammable liquids and are used for moving fluid to the point of use. They have several features for safety. They close automatically after tilting or pouring, they have a pressure relief valve to vent vapor, they have a flame arrestor in the spout, and in the event of a flame on the outside, the arrestor absorbs heat and prevents the flame from passing to the inside of the can. Safety cans have leak-resistant designs.

Plunger Cans Plunger cans are designed to wet cleaning cloths or wipes with flammable liquid. A shallow pan rests on the end of a shaft that is spring supported on the top of the can. By placing a cloth or wipe on the pan and pressing down, a small amount of fluid is pumped into the cloth through the dispensing shaft. Excess fluid drains back into the can.

Cleaning and Dip Tanks There are many fire protection features for cleaning and dip tanks. Tanks vary in size, capacity, and design features. They have covers that protect the fluid from ignition in a fire. Some have foot-operated lids that close when no one is stepping on the lever that opens the lid. Others are normally open and have fusible links that melt at relatively low temperatures, causing the lid to close. Some have drain boards so that dripping fluid from washed parts stay in the tank. Additional protection for large tanks includes sprinklers and automatic drains to holding tanks that operate in the event of a fire. Other fire extinguishing equipment may be needed.

Waste Cloths and wipes contaminated with flammable liquids should be stored in self-closing containers. Waste containers should be small to limit the quantity accumulated, and they should be emptied regularly to prevent spillage outside the can. A foot lever opens a lid and the lid closes when the lever is released. Other design features prevent heat transfer to the contents.

Warehouses and Other Facilities

There are many fire protection problems in warehouses. One should reference applicable NFPA codes and other sources for more details about particular materials. Some important factors for fire protection in warehouse storage are type of commodity, ease of ignition, rate of fire spread, and rate of heat produced. Other factors are quantities of material stored, how they are stored, height of storage, and accessibility. Distance to other commodities also can be important, particularly if one commodity is a fuel and another is an oxidizer. All these characteristics help determine the fire hazards and suitable controls.

For warehouse storage, codes group commodities that have similar fire hazard and control characteristics into classes. Standards specify the height to which commodities may be piled because the height of materials affects fire growth, intensity, and control.

Because warehouses have high densities of materials, a combination of extinguishing equipment is needed. Sprinklers are essential. Because water from sprinklers may not reach fires between, under, or within units of stored materials, fire hoses and portable extinguishers may be needed. Still, some materials may need to be moved to gain access to burning units. Sprinkler design standards mandate clearances between stacked material and sprinkler heads to allow spray patterns to develop. Standards also give flow rates, sprinkler head density, temperature ratings of sprinkler heads, water flow rates of auxiliary fire hose, overall water supply, and other requirements for various commodities and classes of commodities. Sprinkler system requirements and recommendations also are affected by type of storage: storage on pallets, in boxes and bins, on racks, in bulk, or in packaged units. Requirements vary somewhat for different types of facilities, such as indoor versus outdoor, cold storage, bulk tanks, or bins.

16-7 LIFE SAFETY

As previously noted, the first priority in a fire is protection of human life. Life safety deals with providing people with (1) a reasonable degree of safety from fire in a facility and (2) an adequate opportunity to exit facilities if a fire occurs. There are many life safety codes adopted by organization and government units, but the one most often cited is NFPA 101 and NFPA 101B.[3] Sometimes codes do not explain the theory or concepts behind them or how they are applied. For NFPA 101, the *Life Safety Code Handbook* supplies such details.

Human Behavior in Fires

Under the stress of a fire situation, people do not always behave logically. The behavior of one person may affect the behavior of others, and the ability to perform correctly during a fire is confounded by incomplete information about fire conditions and routes to safety. Behavior is affected by personal conditions, such as age, mobility, ability to see and hear, and previous training. Physical conditions in a fire, like smoke, loss of power for lights, rate of fire spread, and heat buildup, can affect visibility, options for movement, and decision making. Density of people, the number of routes, capacity of routes, and distance to the exterior can affect movement and travel time. Today, computer modeling systems allow designers to model exiting behavior with some degree of precision and to evaluate some building features related to life safety.

General Principles of Life Safety

The degree of fire hazard for a building determines the risk to occupants. The degree of fire hazard is based on building contents, the rate of fire propagation for the contents, and activities performed in a building. Life safety codes recognize three classes of hazard: low, ordinary, and high. Life safety codes divide regulations by type of occupancy, for example, residential, places of assembly, hospitals, and industrial. Life safety standards vary by hazard class and type of occupancy (refer to Table 16-4).

Provisions of life safety codes address properties of interior finishes, size, number and location of exits, protection of exit routes from fire and smoke, alarm systems, emergency lighting, signage for exit routes, compartmentation, construction, horizontal and vertical openings, extinguishing systems, and other factors. Some of these provisions are summarized and explained in the following text.

Interior Finishes

Interior finishes are the materials that make up exposed interior wall, column, and ceiling surfaces of buildings. Interior floor finishes refer to the floor covering. Finish materials are tested in laboratory procedures for two fire characteristics: (1) how quickly flame spreads across the material and (2) the amount of smoke produced. Interior finishes are divided into three classes, class A, B, or C, determined by controlled laboratory tests that rate the materials. Ratings by class are as follows:

Class A: flame spread, 0–25; smoke developed, 0–450

Class B: flame spread, 26–75; smoke developed, 0–450

Class C: flame spread, 76–200; smoke developed, 0–450

Floor finishes are divided into class I and class II, based on critical radiant heat flux ratings from controlled tests. The *Life Safety Code* specifies which classes of finishes are allowed for each occupancy and surfaces for exits, access to exits, and other spaces.

Means of Egress

Many factors affect the ability to egress and the time required to do so. A means of egress is a continuous and unobstructed way of travel from any point in a building or structure to a public way (street, alley, or other similar parcel of land open to the outside air). There are three parts to the means of egress: exit access, exit and exit discharge. Exit access is a path leading to an exit. An exit is that portion of a means of egress that is separated from all other spaces of a building or structure by construction or equipment to provide a protected way of travel to the exit discharge. It may consist of doorways, stairs, ramps, corridors, or similar components that are bounded by walls, floors, and doors. An exit is bounded by one or more entrances to it and one or more doors to leave it at ground level. An exit discharge is the last segment of a means of egress between the protected exit and the land outside.

The code specifies a number of attributes for means of egress, such as capacity, number, travel distant to exits, discharge from exits, illumination, emergency lighting, and marking (such as signs and their features). Based on occupancy, it also specifies characteristics of means of egress components (doors, doorways, stairs, ramps, corridors, etc.). For example, the occupancy determines what panic hardware and fire exit hardware is acceptable. It specifies details for revolving doors, turnstiles, sliding doors, illumination (including emergency lighting), and other components.

Capacity The capacity for means of egress is determined from the occupancy load, which is not less than the number of persons determined from occupant load factors. NFPA 101 lists occupant load factors for various occupancies in square feet per person or square meters per person.

Occupant load is computed from

$$\text{Occupant load} = \frac{\text{floor area}}{\text{occupant load factor}}. \tag{16-5}$$

For example, the occupant load factor for a casino is 11 ft^2 per person and 100 ft^2 per person for an office. Thus, a 10,000 ft^2 casino would have an occupancy load of 909 and the same office space would have an occupancy load of 100.

Occupant load values are used to determine the capacity of components of a means of egress, depending on the occupancy. The total capacity of a stairs, for example, is expressed as

$$\text{Total stair capacity} = \frac{\text{width}}{\text{capacity of means of egress for stairs}}. \tag{16-6}$$

Consider a new health care occupancy, which must have a capacity of means of egress for stairs of 0.3 in per person and 0.2 in per person for doors, ramps, or horizontal exits. Thus, stairs that are the minimum 44 in wide each would have a capacity of 44/0.3 = 146 people. If a floor has an occupancy load of 200 people, there would need to be two stairs or wider stairs to meet the occupant load. Other components of the means of egress would require similar analysis.

Number of Means of Egress The minimum is two. For occupant loads between 500 and 1,000, three are required, and for occupant loads more than 1,000, there must be four.

Exit Access Occupants should be able to travel to an exit without obstructions. Some occupancies have distance limits for dead-end routes to an exit, but dead ends should be avoided. Routes should not require passage through doors that can be locked and should not pass through areas of more severe fire hazard. Maximum travel distance permitted from any point to an exit varies with occupancy and whether the building has a sprinkler system. Minimum corridor widths vary with occupancy, but are generally 36 in or more. If access involves use of stairs, the stairs must meet design standards.

Width The minimum width of any means of egress is 36 in and other specifications may apply to egress components.

Stairs The minimum width clear of all obstructions for stairs is typically 44 in. Minimum tread depth is 11 in, and riser height can be no more than 7 in. Headroom must be at least 6 ft 8 in, and the maximum height between landings is 12 ft.

16-8 FIRE DETECTION AND ALARM SYSTEMS

Fire Protection

Fire protection refers to methods for controlling and extinguishing fires. It involves working against time. Figure 16-7 illustrates the process. Indicators of combustion are smoke, flame, and heat, which must be detected in some manner. Then warnings are needed to begin appropriate action for preservation of life and property. The actions needed are exiting or getting people to safety and fighting the fire. The fire-fighting objectives are organized to minimize the amount of property involved and to achieve extinguishment.

Fire Detection and Alarms

There are many kinds of equipment for detecting fires and giving alarms. The devices may be quite simple, applying only to certain aspects of the process. Devices may depend on human activation or may be automatic; they can be combined in sophisticated sensor, annunciator, and alarm systems. Systems generally require regular testing to be sure that components are working properly. Systems can be computer controlled. The computer may perform internal checks constantly for component failures and report which ones are not working properly. A number of NFPA codes establish standards for sensor and alarm components and systems.

There are several kinds of detectors. There are detectors for heat, smoke, flame, and gas content. Each type is suited to particular applications, depending on the type of fire

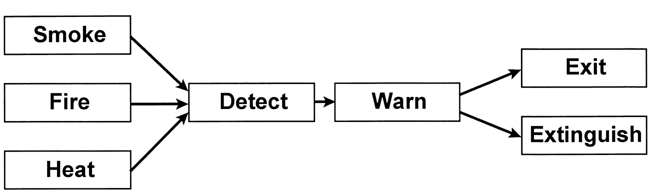


Figure 16-7. Typical actions in response to a fire.

that can occur and the kind of—flammable or combustible materials present. Placement of detectors during installation can be critical. Some require more maintenance than others, and testing is essential to ensure their reliability.

Heat Detectors There are several kinds of heat detectors. They include fixed temperature detectors, rate-of-rise detectors, rate compensation detectors, and others.

Fixed Temperature Fixed temperature heat sensors are designed to operate when a preset temperature is reached. They are available in a variety of temperature settings. Because there is some mass in the sensor, the fixed temperature sensors take some time to respond to conditions. The air surrounding the device will reach the trigger temperature at some time before the sensor elements do. The time lag depends on the device, and because of the lag, fixed temperature sensors are not suitable for fires that develop quickly.

Many fixed temperature sensors depend on fusible elements made from metal that melt at a preset temperature. The break in an element can be coupled mechanically or electrically to other action, such as turning on sprinkler heads or an alarm system.

Another type of fixed temperature element uses two continuous wires, separated by insulation. When a predetermined temperature is reached, the insulation melts and the wires come into contact, which can activate an electrical circuit.

A third type of fixed temperature element uses bimetallic strips or disks. The two metals forming the strip each expand at different rates with temperature increases, which causes the strip to bend or the disk to snap to a different curvature. The movement is coupled to electrical circuits.

Rate of Rise Rate-of-rise detectors respond to fires that flame up quickly but do not react to slower changes in ambient temperature that would normally be expected for slow-developing fires. They typically respond to temperature changes on the order of 12°F/min. One design involves two physical phenomena. First, the air inside a tube expands and builds up pressure inside the tube. When the pressure reaches some predetermined level, a switch closes or opens. Second, the tube has a small hole in it that allows expanded air to leak at a controlled rate. The difference between these two phenomena establishes the rate of temperature rise sensed.

Rate Compensation A rate compensation detector responds to a preset temperature, but is less sensitive to thermal lag than a fixed temperature device. Thus, temperatures that increase rapidly and exceed the preset temperature will be detected sooner.

Other Other heat detectors use thermocouples and gas release from solids to sense temperature changes and to trigger switches and controls. In addition, some detectors have multiple elements that respond to both rapidly and slowly developing fires.

Smoke Detectors In many fires, smoke is present before there is a significant heat buildup. As a result, smoke detectors usually detect fire before heat sensors. Smoke detectors operate on one of two principles: ionization or photoelectricity.

Ionization Ionization detectors contain a very small quantity of radioactive material. They ionize the zone of air around the radioactive material, making the air conductive. When smoke particles enter the zone, the conductivity decreases. An electrical circuit that monitors the conductivity can detect sufficient change and trigger an alarm. Ionization detectors are most sensitive to small smoke particles found in high energy, open-flame fires.

Photoelectricity Photoelectric smoke detectors depend on a source and receiver of light. A beam is directed from the source to the receiver or sensor. Smoke particles entering the beam reduce the light arriving at the sensor and scatter the light of the beam. If the receiver is located in the beam, reduction in light is sensed when smoke is present. The reduction can trigger an alarm. If the receiver is located outside the normal beam, the smoke scatters the light, causing some light to fall on the sensor. When sufficient light arrives at the sensor, an alarm is triggered. This principle also applies to several locations. In some types of photoelectric detectors, a vacuum pump draws air from one or more locations to a central sensing device. Any one of the sources can trigger a response from the sensor.

Flame Detectors Flame detectors monitor for certain wavelengths in the field of view of the sensing device. Infrared and ultraviolet wavelengths are most common. These devices are sensitive to the glow from flames or embers. Some infrared sensors are programmed to monitor a wide band of wavelengths; others measure frequency of infrared present in its field of view, such as in a flickering flame. Broadband infrared sensors are susceptible to false readings from sunlight or other radiant sources that are not sources of fire. In such cases, shielding from alternate sources is necessary but should be used judiciously, because if a shielded flame detector cannot see the fire source, it cannot respond.

Gas Sensors These detectors sense the presence of certain gases produced by combustion in most fires. Electrical circuits coupled to sensing devices trigger alarms.

Alarms and Controls There are many kinds of alarm and control devices activated directly or indirectly from detectors or manual signalling devices. Alarms may be auditory or visual. Visual alarms may simply be a light on an annunciator panel located at the entrance to a building or at some central monitoring station. Audio alarms may be continuous or intermittent tones, variable pitch tones, or voice instructions. Alarms may activate fire and smoke control doors or hatches, may release security systems, and may affect elevator controls or heating, ventilating, and air conditioning (HVAC) equipment. Voice communication may be live instructions from a central station or recorded messages from recordings or computer chips. Each application dictates the kind of alarms and controls needed.

16-9 FIRE EXTINGUISHMENT

Fire extinguishment is the application of agents to control fire spread and ultimately to put a fire out. By far the most common agent is water. For some applications, additives enhance the capabilities of water. Other agents are carbon dioxide, halogens, dry chemicals, foams, and other special-purpose agents.

Kinds of Extinguishment

Fire is extinguished by eliminating any or all of the four components that make up the fire triangle and the fire pyramid. For most materials, combustion is stopped if heat, fuel, or oxygen is removed. In addition, if the creation of the hydroxyl radical can be stopped, combustion will not occur.

Portable Fire Extinguishers

Most fires start small and can be extinguished easily during their early stages. Portable fire extinguishers contain small quantities (for ease of carrying and handling) of an extinguishing agent suitable for suppression of small fires. Extinguishers must be located strategically for quick response, be suitable for the kind of fire encountered, and work properly. The user must know how to use them correctly. A variety of extinguishing agents are available. NFPA 10 contains standards for fire extinguishers.

Classes of Fires There are four classes of fires. The classification scheme helps determine what agents in extinguishers are suitable for different fires.

Class A Class A fires involve ordinary combustibles (wood, paper, cloth, rubber, plastics). Extinguishment is caused by cooling or smothering.

Class B These fires involve flammable and combustible liquids, flammable gases, greases, and oils. Extinguishment is accomplished by inhibiting the release of combustible vapors or the development of the hydroxyl radical.

Class C Electrical equipment fires are class C fires. Extinguishing agents for electrical fires must not conduct electricity.

Class D Class D fires involve combustible metals. Extinguishing agents must absorb heat and not react with the metals.

Portable Extinguishers Extinguishers may contain agents that are effective on one or more classes of fires. Labels on extinguishers identify what classes they are suitable for. Extinguisher labels also contain information about effectiveness of the extinguisher. Examples for class A and B fires are 4-A and 20-B, where 20 is better than 4. These ratings only give relative effectiveness and are not absolute ratings; the 20 is not 5 times more effective than the 4 rating. An extinguishing agent may have ratings for more than one class of fire, and each rating may differ in effectiveness.

Extinguisher Requirements Portable extinguishers do not replace fixed extinguishing systems. Standards define the number and distribution of extinguishers. Important considerations are the class of fire anticipated, the occupancy classification, the class (light, ordinary, high) of hazard in the building, the floor area served and the travel distance from any location to an extinguisher. Extinguishers require inspection, maintenance, testing, and record keeping. Standards detail frequencies and procedures for these activities.

Water Extinguishment

Water can cool the burning surface of many materials and can stop vaporization of the material necessary to support combustion. Through a change of state, water takes up much heat, and thus, a water spray applied to the point of combustion is usually more efficient than a solid stream. Water also can extinguish some materials by smothering the fuel and preventing air from reaching it. However, because of danger from electric shock, water may not be suitable for electrical fires. Also, water may react with certain materials and create hazardous chemicals or conditions.

Additives improve the effectiveness of water as an extinguishing agent for certain fire conditions. They may affect viscosity and surface tension, may cause foaming or create other characteristics, and may prevent freezing.

Water Supplies

Engineering of water supplies for fire protection is an important task. Designs must consider the total amount available in a period of time, the rate of supply at various locations, and the distribution. NFPA codes detail water supply requirements for fire protection in communities and special facilities. Standards also cover hydrants, pumps, fire hose, nozzles, and other components of water supply systems for fire protection.

Chapter 10 discussed some hydraulics. Bernoulli's equation is an essential engineering principle in fire hydraulics. Losses in pipes, fittings, and other components are adjusted to equivalent pipe length for use in Bernoulli's equation. Distribution systems need regular testing to ensure that water supplies are available when and where needed.

Sprinkler Systems

Sprinkler systems are automatic or semiautomatic extinguishing systems for buildings and other facilities. Studies and experience have shown them to be the most effective means for controlling fires in buildings. In most fires where sprinklers are present, activating only a few sprinklers near the fire is sufficient for control. The cost of sprinkler systems is balanced by reduced insurance premiums and reduced losses if a fire does occur. NFPA codes cover sprinkler systems.

In general, sprinkler systems distribute extinguishing agents to the locations where fires occurs. Sprinkler heads operate independently and determine when they should release the extinguishing agent. Placement of sprinkler heads, type of head, appropriate agent, and proper maintenance and testing are essential to the success of a system.

Kinds of Sprinkler Systems There are many kinds of sprinkler systems. Most are water based. However, they may have other agents.

Wet-Pipe Systems A wet-pipe system contains water under pressure at all times. Any sprinkler head that is opened will allow water to pass immediately. Wet-pipe systems can be damaged by water freezing in the pipes, but antifreeze solution stored in unprotected portions of the piping can prevent this threat.

Dry-Pipe Systems A dry-pipe system contains air or nitrogen under pressure at all times. A valve separates water supplies from the dry pipes. An open head reduces the pressure in the gas-charged pipes and allows the valve to open, releasing water to the open sprinkler head and the fire. Dry-pipe systems are suitable for areas subject to freezing. Compared with wet-pipe systems, dry-pipe systems respond more slowly to a demand for water at a sprinkler head, and more heads are likely to open in a fire. Special features prevent inadvertent operation of the water valve.

Preaction Systems This is a special form of dry-pipe system. The piping may or may not be under pressure. Sensors in the protected area besides those at each sprinkler head sense a fire and open a valve to fill the pipe with water. The special sensors operate before those in the sprinkler heads. This design reduces the delay found in a dry-pipe system.

Combined Systems These systems combine features of a dry-pipe system and a preaction system. Pipes are filled with air under pressure. Supplementary sensors open a water valve and air exhaust ports. This allows the piping to fill completely with water before the sprinklers open.

Deluge Systems A deluge system is similar to a preaction system. All sprinklers are open at all times. Fire detecting devices activate the water valve, allowing water to emerge from all sprinkler heads.

Other Systems Some systems are designed for limited water supplies and have one or more limited capacity pressure tanks to supply water. Related systems produce a water curtain to protect outside walls. Other variations may provide reduced protection. An example is fixed water spray protection to provide cooling for tanks exposed to fire.

Components The main components of a sprinkler system are piping, sprinkler heads, and hangers. Piping distributes water throughout the system. Its main components are risers (major vertical pipes), crossmains, and branches. Hangers of various types support the components. The branches extend from the cross mains, and the sprinkler heads attach to branches. There are many kinds of sprinkler heads, the features of which affect how quickly they open and the spray pattern and distribution of water developed. Fusible links activate most sprinkler heads. The sprinkler code contains standards for all system components.

Sprinkler System Design

There are two methods for designing sprinkler systems. One is hydraulic design; the other works from tables, charts, and data provided in the code. The code specifies the water pressure required at each head, and achieving those pressures ensures the proper water flow rate at the heads. Selection of sprinkler heads is important to get the water where it is needed and to make sure that all areas or locations are protected.

Hydraulic Design In hydraulic design, calculations must show that all head pressures will be achieved when water at some pressure and flow rate is applied at the inlet to the system. Hydraulic designs normally reduce system components and costs compared with the table method. Computer programs help to analyze sprinkler designs to determine whether they meet hydraulic requirements and to simulate performance. The general formula in hydraulic design of sprinklers is

$$P_i \geq P_s + P_f + 0.434h, \tag{16-7}$$

where

P_i is the pressure at the system inlet (pounds per square inch),

P_s is the pressure at the sprinkler head of interest (pounds per square inch),

P_f is the friction loss from pipe length, bends, valves, and other fittings (pounds per square inch), and

h is the vertical rise from inlet to sprinkler head (feet).

Computer programs help analyze sprinkler designs to determine whether they meet hydraulic requirements.

Table Method Tables, charts, and other data in the code define what size pipe is needed, how many branches can be on a cross main, and how many sprinkler heads can be on any branch. They also specify the maximum distance between sprinkler heads and between a sprinkler head and a wall, the maximum distance between branches, and the maximum area any one head may serve.

Criteria differ by type of hazard. For the table method, a trial-and-error approach will determine the minimum number of sprinkler heads and other elements necessary to meet the requirements.

Fire Suppression Systems

Suppression systems that do not use water or modify properties of water are useful in particular applications. One should refer to applicable standards for design and use of these systems and agents, which include carbon dioxide, halons, dry chemicals, foams, and combustible metal agents.

Carbon Dioxide Carbon dioxide is stored under pressure as a gas or liquid. It extinguishes by reducing the oxygen content of air and by cooling. It is most suitable for class B fires. It is also useful, but less effective, for class A fires. It can be toxic, it has a noisy discharge, and in enclosed spaces, it can reduce oxygen content for breathing. Carbon dioxide can be piped from storage containers to points of application. Application is by filling an entire enclosure (total flooding) or by local application to burning material.

Halons Halons are hydrocarbons in which one or more hydrogen atom is replaced by atoms from halogens, such as fluorine, chlorine, bromine, or iodine. A variety of halons have been used for fire suppression, particularly in clean rooms and for protecting electronic and computer systems. Some were discontinued because of toxicity and corrosion effects. Today, two halons are in general use: halon 1211 (bromochlorodifluoromethane) and halon 1301 (bromotrifluoromethane). Extinguishing involves interruption of the hydroxyl radical of combustion. Effectiveness is a function of many factors. Halon 1301 is best suited for total flooding applications, whereas halon 1211 is well suited for local application systems. Halons are normally delivered under pressure with nitrogen. Low concentrations seem to have little toxic effect on humans, but do contribute to environmental problems (ozone depletion). The design of halon systems must include allowable exposure times and concentrations.

Studies have determined that halon 1301 has a high ozone depletion potential and therefore is detrimental to the environment. Although the U.S. Environmental Protection Agency allows existing halon 1301 systems to stay in service, new installations are discouraged. To reduce release of halon into the atmosphere, pressure and puff tests or door fan tests replace previously used full-flooding halon acceptance tests. Some new agents are replacing halon 1301 and conventional sprinklers and carbon dioxide suppression systems or new water mist systems may be viable alternatives.

Dry Chemicals There are a number of dry chemicals that are effective in extinguishing fires. They are most effective for flammable liquids and electrical fires. Certain types are also effective for ordinary combustibles. The ingredients are not toxic. They are stable materials in fine powder form. They act primarily by smothering, cooling, and shielding fuel from the radiant heat of a flame. They are expelled by a gas, such as nitrogen, under pressure.

Foams Foams are gas-filled bubbles formed from water-based and other materials. They are primarily used on flammable or combustible liquid spills and fires. The foam forms a layer that prevents vaporization of the liquid. They are used also in applications involving class A and class B materials. Some foams are called high expansion, because they expand in volume by factors of 100 to 1,000. These foams can fill locations that are difficult to reach. The foams are applied by mixing materials in nozzles or foam makers. Fixed foam systems can be actuated automatically. Portable equipment is used for aircraft rescue and industrial fires. The general design formula for high-expansion foam systems for surface fires of flammable and combustible liquids with flash points higher than 100°F is

$$R = \left(\frac{V}{T} + R_s\right) \times C_N \times C_L, \tag{16-8}$$

where

R is the rate of foam discharge (cubic feet per minute),

V is the submergence volume (cubic feet) or volume of space to be protected,

T is submergence time (minutes; normal range from design standards is 2–8 min),

R_s is the rate of foam breakdown by sprinklers (cubic feet per minute),

C_N is the compensation for normal foam shrinkage (normally approximately 1.15), and

C_L is the compensation for leakage around door openings and so on. C_L varies from 1.0 to 1.2.

R_s is normally determined from test data. Where data are not available, R_s may be estimated from the total discharge (gallons per minute) from the maximum number of sprinklers expected to operate times 10.

Combustible Metal Agents For combustible metal fires, agents are available that will not react with the metals. They are generally specific to particular metals; no one agent is suitable for every kind of combustible metal. Most agents are proprietary. Some non-proprietary agents, such as talc, sand, soda ash, and others, vary in effectiveness, but may be useful in certain applications.

16-10 FIRE DEPARTMENTS

In the United States, public fire departments, whether paid or voluntary, provide most fire protection services. Fire departments play important roles in prevention of fires and enforcement of code, training and education of fire fighters and the community, handling communication of fire alarms and other emergencies, responding to fires, and reporting and administration activities. Today, fire departments are likely to respond more often to nonfire than fire emergencies. Hazardous materials and emergency medical responses have become an important part of fire department operations.

There are many opportunities for engineers to contribute to fire department effectiveness. Engineers are needed for design of water systems, site location for response units, modeling and monitoring response times and capabilities, design of fire equipment, and designing alarm and communication equipment and systems.

In-Plant Organizations

Many industries and large facilities cannot depend solely on public fire departments. Much effort is needed within private organizations to ensure that fire prevention and protection is adequate. Many organizations have fire brigades. They handle immediate responses to fire calls, conduct training of employees, and conduct simulations and fire drills. They monitor facilities for fire hazards, check exit routes to make sure they are clear, and may handle inspection and testing of extinguishers, detectors, and other equipment.

Mutual Aid Agreements

Mutual aid agreements are statements that one fire protection organization will assist another and vice versa when major responses are needed. This reduces the personnel and equipment required by any one organization for severe situations. Not only do public fire departments establish such agreements, but many companies set them up with local departments and other nearby companies.

EXERCISES

1. Toluol (molecular weight = 92.13) will be used as a solvent in an operation. Compute the volume of vapor (cubic feet) produced by the evaporation of 1 gal of liquid.
2. Using a dilution factor of 5 to account for nonuniform mixing, what ventilation rate (cubic feet per hour) will be required to keep toluol from reaching the LFL, if 3 gal are evaporated each hour?
3. Eight gallons of turpentine are lost through evaporation because of a spill in an enclosed factory room. The room is 50 ft long, 120 ft wide, and 20 ft high. Using a dilution factor of 3 for unequal mixing, determine if there is a danger of fire if all of the turpentine evaporates.
4. A drying oven has a volume of 50,000 ft^3. A production line runs through it. Parts suspended from the line are dipped in a degreasing tank and drained before entering the oven. The oven is vented with exhaust ventilation and air is replaced by clean air at a rate of 3,000 ft^3/min. When the line and oven are running, 3 gal/hr of solvent are evaporated from the parts. At the beginning of the shift, there is no vapor present in the oven. A design distribution constant $K = 4$ is used to allow for incomplete mixing of vapor in the oven. The solvent has a vapor equivalent of 23 ft^3/gal. The LFL and UFL for the solvent are 1.4 and 8.3, respectively.
   - **(a)** Assume that at startup there is no delay in the solvent soaked parts filling the oven. How long will it take after startup before the concentration of solvent in the oven reaches 100 ppm?
   - **(b)** What will the concentration of solvent vapor be in the oven after 1.5 hr?
   - **(c)** If the line starts but the exhaust ventilation system is not turned on, how many gallons of solvent will evaporate before a flammable mixture is reached? Assume uniform distribution of vapors.
   - **(d)** If the line stops but the exhaust ventilation system keeps running, how long will it take to reduce a 200 ppm concentration to 50 ppm? Assume the evaporation stops when the line stops.

5. The area formed by combustibles in a manufacturing facility is 35 × 40 ft. There are curtain boards extending 12 ft from the ceiling that end 15 ft above the floor. What area of roof venting is needed between curtain boards spaced 175 ft apart?

6. An office room measures 40 × 60 ft. It contains 2,000 lb of paper stored openly, 1,500 lb of paper stored in file cabinets, and 1,200 lb of paper manuals stored in open book shelves. Assume the paper has a heat content of 8,000 BTU/lb. What is the total fire load in the room?

7. A three-story motel is on the drawing board. The accompanying illustration shows guest room layouts for each floor. Consider only the residential section. Assume the lobby is unoccupied. Determine the following from the current *Life Safety Code* (NFPA 101®):

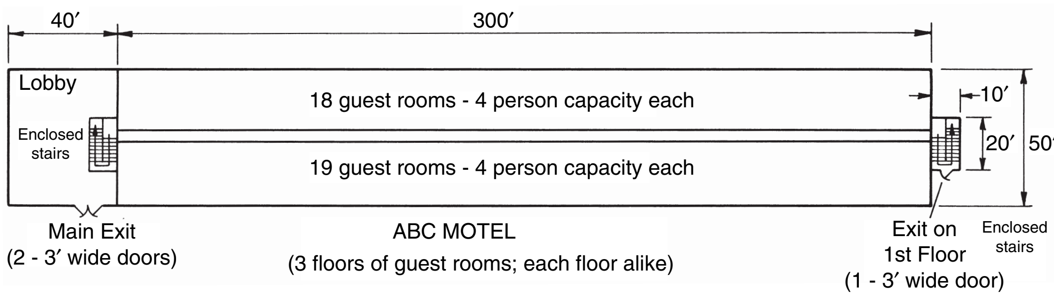


Diagram for Exercise 7.

(a) What is the occupant load for determining the amount of fire exits?

(b) What exit capacity is required for each floor of the motel?

(c) Is the travel distance to exits from any room exceeded?

(d) Assume the travel distance for rooms in the center of a floor is too long. What redesign alternatives would make the travel distance satisfactory.

(e) What fire-resistance rating must the walls enclosing the stairways have?

(f) What fire-resistance rating must the walls between guest rooms have?

(g) The designers are considering carpet for the corridors. The manufacturer certifies that the carpet selected has a flame spread rating of 81. Can it be installed in the corridors?

(h) Could the same carpet be used in the guest rooms?

(i) Do the exit stairs and door widths satisfy the code?

8. A sprinkler head has a discharge rate of 22.5 gal/min and a coefficient $K = 5.65$. What pressure is required at the sprinkler head?

9. For the wet-pipe sprinkler line shown in the accompanying diagram, what pressure is required at the inlet if the discharge rate must be 22.5 gal/min and the sprinkler head has a coefficient $K = 5.65$? Assume that fittings connecting two different sized pipes are the size of the smaller pipe. Assume that pipe diameters, d, equal the nominal diameters.

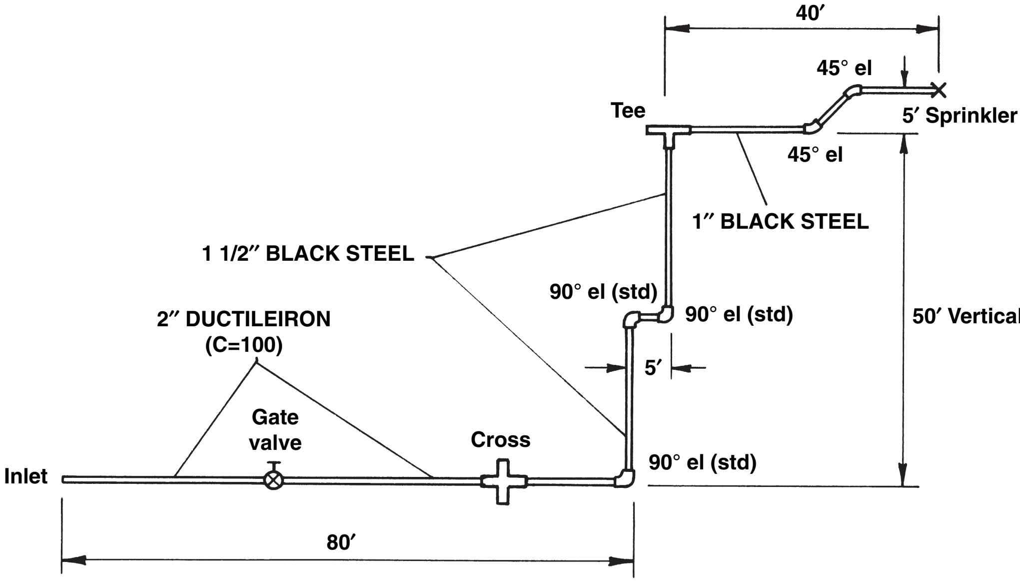


Diagram for Exercise 9.

10. For the facility layout shown in the accompanying sketch, complete the sprinkler system layout using NFPA 13. The cross mains are already located, placed on one side of the building, and the branch lines should extend across the room from the cross main.

(a) Locate branch lines and sprinkler heads on branch lines. Dimension locations along branches and between branches and walls.

(b) How many sprinklers are required for each of the three zones to meet all design criteria?

(c) What size copper tubing is required for the branch lines in the extra hazard zone?

11. Identify the occupancy classification for

(a) a retail store

(b) a grade school

12. What type of construction is

(a) a frame structure that uses standard wood studs?

(b) a frame structure that uses steel studs?

(c) a structure with 8-in concrete block walls and partitions?

REVIEW QUESTIONS

1. Describe total fire losses for the United States each year in cost and deaths.
2. What is the cause of most deaths from fires?
3. For what age groups is death from fire most prevalent?
4. Describe the relationship between alcohol use and fires.
5. What is the leading cause of civilian fires?
6. What are the two leading causes of industrial fires?

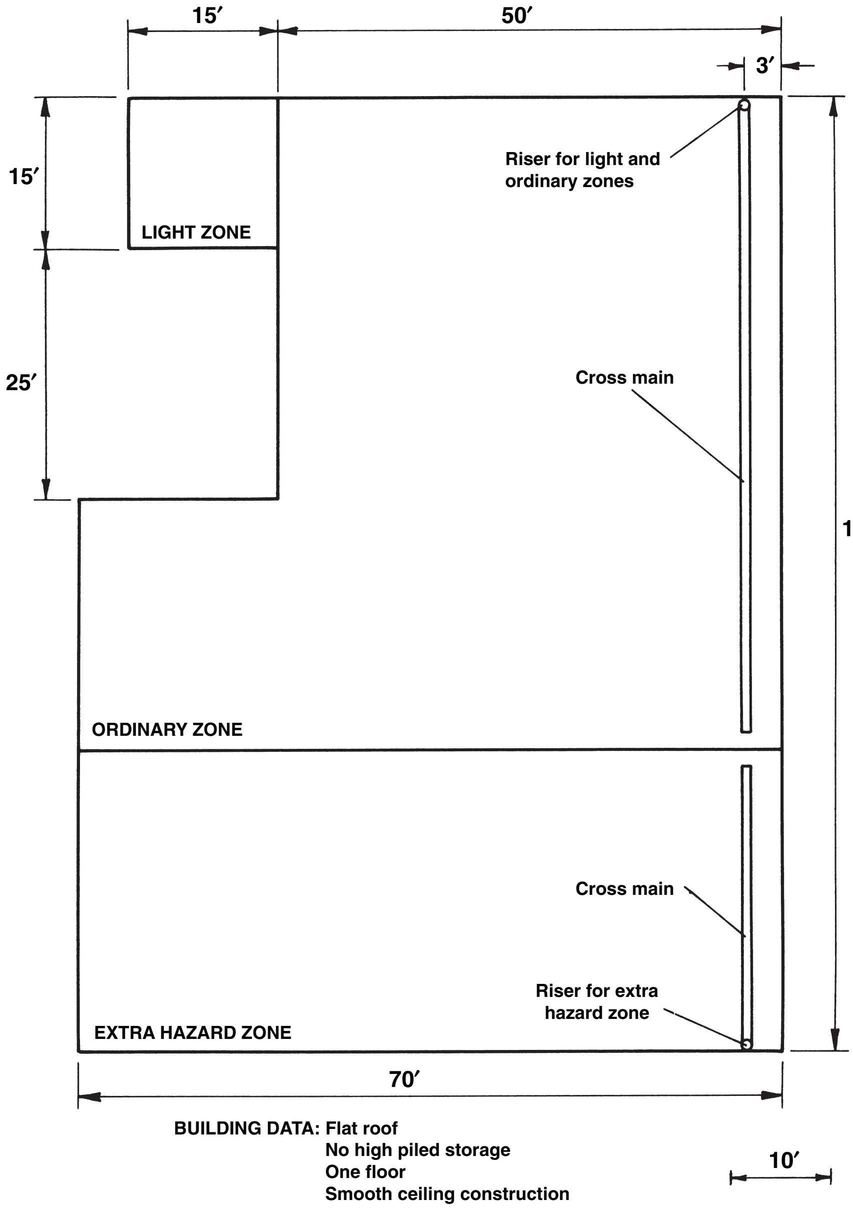


Diagram for Exercise 10.

7. To what extent are arson and incendiary fires a significant element in the fire losses?

8. What organization is the main source for fire codes and standards in the United States?

9. Define

(a) combustion

(b) ignition

(c) spontaneous combustion

- **(d)** the fire triangle
- **(e)** the fire pyramid

10. Name four methods for controlling combustion and for extinguishing fires.

11. Name four products of combustion and the danger of each.

12. Describe the movement of hot gases from a fire in a horizontal building and a vertical building.

13. Define or characterize each of the following for a flammable or combustible liquid:

- **(a)** flash point
- **(b)** fire point
- **(c)** vapor pressure
- **(d)** vapor volume
- **(e)** lower flammable limit
- **(f)** upper flammable limit
- **(g)** flammable range

14. Define

- **(a)** flammable gas
- **(b)** char

15. Describe the NFPA symbol and method for identifying hazardous materials and their properties.

16. What are the objectives for fire safety in buildings?

17. Identify at least three requirements for site planning that are important for fire safety.

18. What are four characteristics of buildings that are important in designing for fire safety?

19. Explain the following:

- **(a)** compartmentation
- **(b)** fire load
- **(c)** fire resistance rating
- **(d)** flame spread rating

20. How can the buildup and lateral movement of heat from a fire in a single story factory be minimized?

21. What are the fire hazards of welding and cutting and how can they be controlled?

22. Identify at least four ways to minimize fire hazards of flammable liquids stored indoors.

23. What is life safety?

24. What aspects of building design do life safety features address?

25. Define

- **(a)** means of egress
- **(b)** exit
- **(c)** exit access
- **(d)** exit discharge

(e) exit capacity
(f) occupant load

25. Name at least four kinds of detectors for fire protection and describe the function of each.

26. Describe the materials included in each for the four classes of fires.

27. Identify and describe five kinds of sprinkler systems.

28. What are the two approaches for designing sprinkler systems?

29. How does each of the following accomplish fire extinguishment?

(a) water
(b) carbon dioxide
(c) halons
(d) dry chemicals
(e) foams
(f) agents for combustible metals
(g) water mists

NOTES

1 Stein L., *The Triangle Fire*, Carroll & Graf Publishers, Inc., New York, 1962. Von Drehle, David, *Triangle—The Fire that Changed America*, Grove Press, New York, 2003.

2 NFPA 704, *Identification of the Hazards of Materials*, National Fire Protection Association, Quincy, MA.

3 NFPA 101, *Life Safety Code* and NFPA 101B, *Means of Egress*, National Fire Protection Association, Quincy, MA.

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