Combustion, Fire, and Flammability

OBJECTIVES

After studying this chapter, you should be able to:

- Describe how the U.S. fire incidence database enables development of a national profile of fires and fire losses.
- Define the process of combustion.
- Explain flammability, in terms of both fire properties and practical application.
- Explain the nonflaming and flaming stages of fire.
- Discuss the fire tetrahedron and explain how it is a focus for a unified view of fire initiation, growth, and termination.
- Discuss the terms fire consequences, hazard, and risk.
Introduction

Understanding fire types and the characteristics of each type is fundamental in improving fire safety. The United States has a unique capability to track the frequency, severity, and nature of fires. The National Fire Incident Reporting System (NFIRS) is the world’s largest national database of fire incident information [1]. Each year, approximately 23,000 fire departments in 50 states and the District of Columbia report information on fires in their jurisdictions. The input data to NFIRS reflect 75 percent of all reported fires that occur annually. The U.S. Fire Administration, the U.S. Consumer Product Safety Commission, and the National Fire Protection Association publish complementary analyses of the NFIRS data. These analyses enable the fire safety community to quantify the largest contributors to the United States’ fire problem, identify emerging threats to fire safety, and estimate the effectiveness of new standards and code provisions.

To illustrate the power of this database, consider the analysis of fires involving residential upholstered furniture and beds as the first item ignited (Table 6-1). The two shaded rows in Table 6-1 show that, while these fires represented only 5 percent of all residential fires, they led to one-third of all fire deaths. A subsequent analysis by John Hall of NFPA [2] estimated the fire losses for fires in which residential upholstered furniture was not the first item ignited, but was the principal amplifier of the hazard resulting from the initial ignition of another item. These additional contributions to fire loss are reflected in the upper “Upholstered Furniture” row. (A similar analysis has not been performed for mattresses and bedding.) The combined data show that furniture and bed fires are seven times more deadly and three times more likely to result in an injury than the average household fire.

Figure 6-1 shows that NFIRS compiles information that allows identification of the prevalent ignition sources. Cigarette ignition of upholstered furniture is the largest single cause of fire deaths [3]. Figure 6-2 demonstrates yet another dimension of the data—namely, that nearly two-thirds of the U.S. fire deaths that began with upholstered furniture resulted from fires that had extended beyond the room of fire origin. These fires are interpreted as having passed the point of room flashover.

The knowledge gained from these analyses enables fire scientists to examine the most relevant fire phenomena, the fire service to align its response capability and operating procedures with the most important fires, and fire codes and standards developers and regulators to guide the marketplace toward effective solutions to fire problems. Supporting all these members of the fire safety community is a common understanding of fire and its consequences. This chapter begins the presentation of that understanding.

<table>
<thead>
<tr>
<th>Fires</th>
<th>Deaths</th>
<th>Injuries</th>
<th>Direct Property Loss ($) M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>373,900</td>
<td>2650</td>
<td>12,890</td>
</tr>
<tr>
<td>Upholstered furniture [3]</td>
<td>9240 (2%)</td>
<td>630 (24%)</td>
<td>966 (7%)</td>
</tr>
<tr>
<td>Mattresses and bedding [4]</td>
<td>7040 (2%)</td>
<td>500 (19%)</td>
<td>690 (5%)</td>
</tr>
<tr>
<td>Overall</td>
<td>10,260</td>
<td>371 (14%)</td>
<td>1340 (10%)</td>
</tr>
</tbody>
</table>
Combustion

Combustion is an exothermic chemical reaction between a fuel and an oxidizer resulting in the generation of substantive heat and often light. Interestingly, dictionaries often use the same words to define fire. “Fire” generally conveys a connotation of being potentially uncontained, unwanted, and destructive—which is the context for this text. (There are some cases of positioned, intentional, and beneficial fires, such as those set to clear the rubble from last year’s crops.)
To understand the content of this and the following chapters, it is important to understand the definition of combustion. Each of the following words or phrases is central to differentiating combustion in general, and fire in particular, from other processes.

- **Chemical reaction.** Combustion involves chemical change: the arrangements of atoms in the combustion products are different from the arrangements in the reactants. Thus, while a liquid material may be vaporized during combustion, the phase change in itself is not combustion.

- **Exothermic.** The overall combustion reaction gives off heat. This heat can raise the temperature of additional reactants, thereby continuing the combustion process; expand gases that drive turbines; or burn skin.

- **Fuel.** Combustible materials can be gases (e.g., methane), liquids (e.g., gasoline), or solids (e.g., wood). Noncombustible materials, such as helium, water, and stone, do not satisfy this definition. The nature, intensity, and duration of the combustion are in part determined by the fuel chemistry and supply.

- **Oxidizer.** The most common oxidizer in combustion is the oxygen present in air, and this is especially true for fires. As is true for the fuel, the nature, intensity, and duration of the combustion are in part determined by the oxygen supply. A restricted supply of air or the depletion of oxygen in the air by the combustion, referred to as vitiation, can reduce the burning rate and alter the nature of the combustion products. Combustion
does not necessarily require oxygen molecules or even oxygen atoms. An example of the former is the use of potassium perchlorate (KClO₄) in fireworks and munitions; an example of the latter is the reaction of CF₃Br (halon 1301, an effective extinguishant for hydrocarbon fires) with magnesium. Other chemicals self-combust—these are presented in the chapter on solid combustibles.

- **Substantive heat.** Combustion reactions are a subset of exothermic oxidation reactions. Some exothermic oxidation reactions are extremely slow. For example, rusting never increases the temperature of the metal more than a degree or so above that of the surroundings and may go unnoticed for months. By contrast, a combustion reaction generates heat faster than it is dissipated, causing a substantial temperature rise (at least tens of degrees Celsius, and often 1000 °C or more).

- **Light.** When the combustion-generated temperature is high enough, visible light is emitted from the combustion reaction zone. This can be seen as a glowing solid, such as a fireplace ember, or in the gas phase, such as a flame.

As can be gathered from these definitions, the initiation and continuance of combustion or a fire require four components, as depicted in the fire tetrahedron (Figure 6-3):

1. Fuel
2. Oxidant
3. Elevated temperature (heat)
4. Chemical chain reaction

The balance among these components is critical. Too small a concentration of fuel may not be sufficient to propagate combustion, even if plenty of air is available. Similarly, fuel and air may not react if the temperature is too low.

![Figure 6-3 The fire tetrahedron.](image)
The following is a brief presentation of combustion as it pertains to fires. For more detailed information, refer to references such as [5], [6], and [7].

Flaming and Nonflaming Combustion

ISO 19706 defines a set of phenomenological stages of a fire [8]:

1. Nonflaming
   a. Self-sustained (smoldering combustion; also called glowing combustion)
   b. Oxidative pyrolysis from externally applied thermal radiation or conduction
   c. Anaerobic (oxidizer-free) pyrolysis from externally applied thermal radiation or conduction

2. Well ventilated flaming free burning

3. Underventilated flaming
   a. Small, localized fire, generally in a poorly ventilated compartment
   b. Post flashover fire

The existence, sequencing, and duration of these phenomenological stages can vary from fire to fire. The roles of these stages are best explained using examples. Figure 6-4 depicts the timeline for two hypothetical fires. The curve in blue is for a fire occurring in a typical residential bedroom with the door open.

**Figure 6-4** Rate of heat release from two bedroom fires under different ventilation conditions. Blue curve: Door open and windows initially closed. Red curve: Door and windows initially closed. Dashed red curve: Door and windows remain closed.

- A. Smoldering ignition of the bed by a cigarette; some oxidative pyrolysis
- B. Smoldering transition to well ventilated flaming; some oxidative pyrolysis
- C. Room flashover; ventilation-limited flaming; extensive pyrolysis
- D. Window breaks from the heat; burning no longer ventilation-limited
- E. Maximum mass burning rate; extensive pyrolysis
- F. Fuel begins to run out; extensive pyrolysis
- G. Flames out; rubble smoldering
- H. Door is opened
and the windows closed. The curves in red are for a fire in the same room with the door initially closed. The following sections of this chapter provide a general description of the stages of these fires. More detailed information on principles of fire phenomena is presented in the subsequent chapters.

**Fire Initiation**

We are surrounded by combustible items (e.g., trees, beds, clothes, cars, and even our own bodies) that are in contact with the oxygen in air. Why do these fuels not ignite and burn? How can reactants—for which we can write a balanced, exothermic chemical equation—coexist without consuming each other?

The answers to these questions lie in chemical kinetics, as introduced in the Physical and Chemical Change chapter. At room temperature, very few collisions between fuel molecules and oxygen molecules have enough energy to break chemical bonds. At the macroscopic level, this means that the reaction rates of common combustibles with oxygen are extremely slow at room temperature. However, these reaction rates increase sharply with increasing temperature. If a sufficiently high temperature is created in even a small region where both the combustible material and oxygen are present, **ignition** will occur. The oxidation process will accelerate in this region, generating its own heat and supply of free atoms and free radicals. The heat will then spread to adjacent areas, and the combustion will be sustained—that is, there will be a fire.

Depending on the ignition source, a fire can begin as smoldering combustion, perhaps progressing later to flaming, or the fire can begin directly as flaming.

Smoldering is the most common initial stage of combustion in fires that lead to injury or death (Figure 6-1). Smoking materials (cigarettes), hot embers and ashes, space heaters, and overheated electrical equipment are potential ignition sources for smoldering. Once ignited, upholstered furniture containing cotton fabrics and cotton or polyurethane foam padding can smolder for an hour or more. A large pile of wood chips, sawdust, or coal can smolder for weeks or even months. Peat fields have smoldered for decades.

Smoldering generally is limited to porous materials that can form a carbonaceous char when heated. The oxygen in the air slowly diffuses into the pores of the material, where it reacts directly with the solid carbon and generates heat. These porous materials are poor conductors of heat (i.e., good thermal insulators); therefore, even though the combustion reaction occurs slowly, enough heat is retained in the reaction zone to maintain the elevated temperature needed to sustain the reaction. The reaction zone within the material can be glowing red, but typically is not readily visible from the outside.

The reaction zone in a smoldering mattress might spread a foot or more from the ignition point or might even consume the entire mattress. At some point, the mattress might suddenly burst into flames. This change in the nature of the combustion typically results from an increase in the temperature of the smoldering zone, often a result of an increase in air flow across the furniture. The mass rate of burning (and the rate of heat release) during flaming combustion is many times higher than during smoldering combustion.

During the smoldering process, adjacent material is also being pyrolyzed by the heat being generated or by the heat from the ignition source. Pyrolysis is different from smoldering in that pyrolysis stops when the heat source is removed, while smoldering generates sufficient heat to continue without external heat input. The combustion products from smoldering and pyrolysis also are different. Pyrolysis occurring due to, e.g., a space heater “cooking” a nearby chair, is oxidative pyrolysis, since there is ample surrounding air. Anaerobic pyrolysis is likely when overheated household power cable maintains contact with wood in the stud space behind gypsum wallboard.

A flame is the result of rapid gaseous oxidation reactions. From Equation 3-2 in the Physical and Chemical Change chapter, the temperature rise for a given heat generation is $\Delta T = \Delta H/mc_p$. For typical combustion reactions, $\Delta H$ is quite large and both $m$ (the mass of air being heated) and $c_p$ (the specific
heat of air, shown in the Physical and Chemical Change chapter) are small. Thus, the temperature rise is large. The yellow-orange glow of the soot in the flame is characteristic of temperatures near 1500 K.

Flames from a condensed (solid or liquid) fuel need gaseous fuel to continue burning. When a condensed fuel, such as a candle or a pool of gasoline, burns, a portion of the heat of the gaseous flame is transferred to the fuel, causing it to gasify. When this gasification occurs without chemical decomposition of the molecules, it is simple evaporation. If chemical decomposition occurs, which is typical of solid fuels, the process is pyrolysis.

**Fire Spread**

The spread mechanism of a fire depends heavily on whether the combustibles are gaseous, liquid, or solid. In the case of a flammable gas, the spread is determined by the extent of mixing of the gas with air prior to combustion as well as by the degree of motion and turbulence of the gas. For a liquid, the spread of combustion depends on whether the combustion occurs in a still pool of liquid, a flowing liquid, a spray, a thin film, or a foam.

A solid might be in the form of a powder, a thin sheet (e.g., paper), or a thick solid object. The speed of fire spread over a solid can be as fast as several
meters per second or as slow as a fraction of a millimeter per second, depending on the conditions. Combustion spreads much more rapidly over thin solids and solids with high surface areas. The spread rate on a vertical solid surface is much faster in the upward direction than in the horizontal or downward directions. The fire spread rate over a horizontal surface depends on whether air currents are moving toward or away from the combustion zone.

In most cases of fire spread, the basic mechanism is the same. A portion of the heat produced by a burning item is transferred, by radiation, conduction, or convection, to an unburned part of the item or to a nearby combustible that is not yet burning. This cool fuel is heated to the temperature at which its pyrolysis is fast enough that the concentration of combustible vapor above the fuel surface exceeds its lean flammability limit. The flames then extend to this region and begin to pyrolyze the next area of cool fuel. Fire also can spread by the melting and dripping of burning material, or by airborne firebrands.

**Fire Ventilation**

Flaming combustion generates the large release of heat that can lead to room flashover, with the degree of ventilation often determining whether flashover is reached or not. When a flaming fire is small and is surrounded by fresh air, the fire can entrain all the oxygen it needs. The fire is said to be well ventilated. As the fire grows, it can reach a point at which it is consuming all the air that can enter the room through, e.g., an open door. At this point, the fire cannot burn any faster; it is ventilation-limited. If the fire is burning in a closed room, the ambient air becomes oxygen-depleted, and this fire also becomes ventilation limited.

During the course of a fire, a ventilation-limited condition can change suddenly to a more nearly ventilated condition. This can occur when the fire breaks a window, an occupant opens a door, or firefighters vent a roof. At this time, the heat release rate of the fire rises quickly to a level determined by the size and location of the new opening.

**Fire Termination**

The fire tetrahedron (Figure 6-3) shows that combustion requires supplies of fuel and oxidant, a high temperature, and reactions that proceed fast enough at this high temperature to generate heat as fast as it is dissipated, so that the reaction zone will not cool down. Any action that sufficiently upsets this balance will extinguish the fire. In practice, most firefighting approaches affect more than one component of the fire tetrahedron. A more detailed presentation of fire extinguishment appears in the *Fire Fighting Chemicals* chapter.

Adding a coolant absorbs heat from and reduces the temperature of the combusting system; that is, the coolant serves as a heat sink. The coolant can be any material with a relatively high heat capacity. It is not necessary for the coolant to absorb heat as fast as the heat is being generated, because the reaction zone in a fire is already losing some heat to the cooler surroundings. In some cases, only modest additional heat dissipation is needed to tip the balance toward extinguishment.

Extinguishment can be accomplished by cooling either the gaseous combustion zone or the solid or liquid combustible. In the former case, the cooling is accomplished by introducing a gas or liquid with a high heat capacity into the flame zone. This mechanism is how carbon dioxide extinguishers work, in addition to displacing or diluting the supply of oxygen. In the latter case, the coolant is applied to the fuel surface, preventing the production of combustible vapors. This is what you accomplish when you douse a campfire with water.

As a simple demonstration of extinguishment by cooling, support a thick, 20-cm-long vertical strip of cardboard from the top and ignite the bottom with a match **Figure 6-6**. The flame will attach to the bottom of the paper and spread rapidly to the top of the strip. Then repeat the experiment, but first soak the top half of the cardboard with water. When the flame reaches the wet section, it is extinguished. The water acts as a heat sink and upsets the balance between heat production and heat loss. The flame cannot heat the cardboard to its pyrolysis temperature in the available time because of heat absorption by the water.

Extinguishment also can be accomplished by introducing a barrier between the combustible
surface and the flame, the source of heat. For example, applying a layer of aqueous foam to a fuel spill cools the surface, shields the surface from the flame radiation, and blocks any gasified fuel from replenishing the flame [Figure 6-7]. In addition, the potential fuel may be separated from the fire by placing a fire blanket over the combustible item. Some fire-retardant additives, when heated, expand to form an insulating layer over the material they are protecting.

Another means of extinguishing a fire is to reduce the availability of oxygen by closing the openings to a burning compartment. This practice constricts the inflow of air, while diluting the existing air with noncombustible combustion products, such as carbon dioxide. [Figure 6-8] shows a simple experiment that demonstrates the principle of this approach. In the left drawing, the glass beaker is held above the fuel surface. Fresh air is entrained into the base of the flame, and the candle continues to burn. In the right drawing, the beaker has been lowered. Less air is entrained into the base of the flame, and the atmosphere surrounding the flame is depleted in oxygen and rich in carbon dioxide from the combustion, causing the flame to extinguish.
The same approaches to interference with the fire tetrahedron can control a fire, keeping it at a manageable level until first responders arrive on the scene. One of the functions of an automatic sprinkler system is to contain fire spread when extinguishment is not possible.
The ignited flames may then expand violently out the doorway, harming any who are nearby—the dangerous condition known as backdraft. This is graphically shown in Figure 6-9, where two photographs, taken only seconds after the compartment window was opened, show the rapid and extreme hazard of a backdraft.

The chemical reactions in flames are sustained by free radicals. Some bromine-, chlorine- and phosphorus-containing chemicals reduce the concentration of free radicals when added to flames and slow down the combustion reactions. Examples include halon fire extinguishants and ammonium phosphate, which is dropped onto forest fires. These approaches can also prevent ignition. A fuse or circuit breaker, recognizing that too much current is being drawn, can prevent an electrical ignition by tripping before any fuel is hot enough to ignite. Some gaseous fire suppressants inert a space by increasing the heat capacity of the air or by chemically interfering with the ignition process before combustion can be sustained (addressed in the Fire Fighting Chemicals chapter).

In many real-world fires, the hazard continues even after the flames have been extinguished. Although the combustion of liquid and gaseous fuels ends very soon after the flames have been quenched, some solid fuel fires leave a hot, porous rubble that can continue to smolder for days. This smoldering is fundamentally similar to the smoldering that occurs in the earliest stage of a fire. However, the mass of smoldering material is considerably larger.

**Two Examples of Room Fires**

For decades, fire scientists have conducted real-scale fires to learn how fires ignite and progress to the point where lives and the integrity of the building are threatened. Figure 6-10 shows a sequence of frames from such a fire test. The furnishings in the family room are a sofa and a loveseat flanking an end table with a lamp. There are draperies behind the sofa.

The fire begins in the corner of the sofa, perhaps as the result of a cigarette that fell into the crack between the seat, arm, and back cushioning. The initial smoldering transitions to flaming, slow at first but growing. At about 60 seconds, the flame is as high as the back of the sofa, and wispy black smoke is rising toward the ceiling. By 1:30, a black smoke layer has spread across the entire room. The bottom of the layer is about 1.5 m from the floor. At 2:50, in the upper layer, flames can barely be seen, but are spreading across the ceiling. This is the
phenomenon called flameover or rollover. The air in the lower part of the room (away from the fire itself) is still relatively cool and clear. However, just after 3 minutes, the upper layer is now so hot that the radiant energy is intense enough to ignite the loveseat in a location that is away from the burning sofa. This is the phenomenon called flashover, the point at which all the combustibles in the room are aflame. The pyrolysis rate of the sofas is very high, and there is not enough oxygen in the room to burn all the gaseous fuel that is being generated.

During the early flaming, the bottom of the upper layer descends below the top of the door frame. Some of the smoke flows out of the room through the upper part of the doorway, while fresh air is drawn in through the lower part. As the burning
accelerates, these two flows increase dramatically, and the smoke from the upper layer is driven into other parts of the building. This threatens the escape capability of people not in the initial fire room. At 3:14, the unburned gases jetting through the doorway are hot enough that they react with the oxygen outside. The turbulent flames surging through the doorway can spread the fire to adjacent compartments. At this time, approximately 3 minutes after the first flames became evident, the building and all its occupants are at risk.

The growth rate of this fire and the time to flashover may be surprising, but are not at all unusual. In fact, some fires reach serious proportions much faster. Figure 6-11 shows images of a dry Christmas tree fire in a small living room. The tree is ignited near the floor, perhaps by an overheated string of decorative lights. The black smoke layer is rolling across the ceiling and down the walls only 8 seconds after ignition. One of the chairs has ignited by 17 seconds, and the room reaches flashover in 26 seconds. By 40 seconds, even the flooring is burning.

If the door had been closed in either of these two fires, the intense thermal radiation from the upper layer would have pyrolyzed material at the same time that the burning depleted the oxygen in the room. Shortly after opening the door, the emerging flames due to the backdraft would look similar to the final frame in Figure 6-10.

Rest assured that there is no simplistic resolution of the disagreements about definitions; however, people who will be practitioners in fire safety need to understand the phenomena they will face.

A first approach to defining flammability derives from what our eyes tell us. Does something ignite? Does it keep burning? Water does not ignite, so it is not flammable. Gasoline is designed to burn in engines, so it is flammable. Hold a match to a 2 × 4 stud and it will not ignite, yet we know wood burns because we have seen houses destroyed by fire.

This suggests a second approach to defining flammability, one that lies in the measurement of fire behavior. Classically, an apparatus is constructed that appears to replicate a fire situation that has caused considerable harm. An ignition source of a chosen size is placed in contact with a specimen of a chosen size for a chosen duration. A quantity, such as the time to ignition or self-extinguishment, the rate of flame spread, or the opaqueness of smoke, is measured. Based on this value, the product from which the test specimen was cut is assigned a flammability rating. More recently, apparatus have been designed to quantify material fire properties, such as the rate of heat release or the minimum radiant flux necessary to spread flames. Reference [9] compiles nearly all of the standard fire tests used in North America.

When one of these tests is accepted, and the use of the test result is incorporated into practice, the test output becomes the definition of flammability. Commercial materials and finished products are then designed to the test, and product specifications are set according to the test.

As can be seen in Reference [9], multiple test methods may exist for the same property (e.g., ignition delay time, rate of flame spread). These do not always give the same result for a given product, nor do they always rank products in the same order. This text is intended to provide a sufficient knowledge of the scientific principles underlying fire that the readers can understand the concepts and metrics of flammability and recognize those actions that can improve a nation’s fire profile and those that do not.

Flammability

In the broadest sense, we as a community use the term flammability to connote how vigorously something burns. The term combustibility is also used in some cases to describe the flammability of certain building construction materials. As we seek a more precise definition of flammability, however, the degree of agreement diminishes. Because the next three chapters treat the fire characteristics of gaseous, liquid, and solid combustibles, here are some thoughts for consideration as you read about fire properties and their meaning in the context of flammability.
Figure 6-11 Frames from a video of a Christmas tree fire in a family room.

Courtesy of National Institute of Standards and Technology.
Fire Consequences, Hazard, Risk, and Flashover

Three definitions regarding the outcomes of fires are used throughout this text (and in the fire literature as a whole):

- A **fire hazard** is a condition with the potential to create harm under a specified set of conditions called a **fire scenario**. An example of a fire scenario is an intoxicated person, alone in an apartment, smoking in bed. The hazard is that he could drop the lit cigarette onto the bed, where it ignites the bedclothes and mattress.

- A **fire consequence** is a fire hazard quantified as to its severity. In this example, the consequence of the fire could be the smoker’s death from inhalation of smoke from a smoldering pillow.

- A **fire risk** is the combination of consequences, each multiplied by the likelihood (probability) of each scenario occurring and the probability that the scenario will result in each consequence. As evidenced in the U.S. fire loss statistics, the risk of fire death from smoking in bed is greater than the risk of death from smoking outdoors.

**Note**

The following data put the concepts of fire risk and fire consequences into perspective. With approximately 400,000 residential fires reported each year and about 100 million households in the United States, it is likely that each of us will see and hear fire trucks in our neighborhood in our lifetime. These fires are consequential to both civilians and firefighters: someone in the United States dies or is injured in a fire every 5 minutes [10].

The consequences of a fire are sharply increased if the fire in a room proceeds to flashover. In physical terms, flashover is the point at which the thermal radiation from a fire and the hot smoke layer becomes sufficiently intense (in excess of approximately 20 kW/m²) that nearly all combustible surfaces in the compartment ignite simultaneously. This point occurs when the temperature of the hot smoke layer under the ceiling approaches 1100 °F (600 °C).

Before a room reaches flashover, the fire hazard is mostly limited to the people within the room and to the room contents, because the fire is localized and little smoke or heat leaves the room. (There might be sufficient smoke flow through a doorway to activate a smoke alarm that is properly placed outside the room.) After flashover, the flow of heat and toxic gases into other spaces in the building is greatly accelerated. In the United States, most fire deaths occur outside the room of fire origin from fires that have proceeded past flashover.

A principal goal of fire safety science, technology, and engineering practice is to reduce the likelihood of flashover. This is equivalent to managing the heat release rate that might occur in a room. The minimum heat release rate for flashover increases with the size of the room and depends on the ventilation in the room. If too little ventilation is available, the fire is starved for air and goes out or the burning generates too little heat for flashover. If the ventilation is excessive, the excess air flow dilutes and cools the smoke, so a larger rate of heat release is needed to reach the critical temperature condition for flashover. The materials of construction and thickness of the ceiling and upper walls are other important factors in determining whether flashover will occur and, if so, how soon.

Reference [2] has compiled quantitative relationships that can be used to calculate the critical fire size for flashover. A point of reference is that a heat release rate of 1 MW will bring an ordinary residential bedroom to flashover, if this intensity is sustained long enough for the extensive radiative ignition to occur, which can be as little as 1 minute. As seen in Figure 6-10, an upholstered sofa can bring a small living room to flashover in approximately 3 minutes from the time of ignition.
Chapter Summary

• Analysis of the data compiled in the National Fire Incident Reporting System database can identify the relative frequency of various types of fires. The knowledge gained from such analyses enables fire scientists, the fire service, fire codes and standards developers, and regulators to provide guidance geared toward reducing losses from fires.

• Combustion is an exothermic chemical reaction between a fuel and an oxidizer resulting in the generation of substantive heat and often light. Interestingly, dictionaries often use the same definition for fire. Fire is a form of uncontained, unwanted, and destructive combustion.

• The flammability of a material or product can be defined by whether it ignites and burns, although flammability is more commonly defined in terms of a measured property in a fire test.

• A fire can proceed through both nonflaming and flaming stages. The nonflaming stages consist of smoldering and pyrolysis (with or without the participation of oxygen); the flaming stages include well-ventilated, under-ventilated, and post-flashover fire.

• The initiation and continuance of a fire require the four components that make up the fire tetrahedron: fuel, oxidant, heat, and chemical chain reaction.

• The reactions that initiate a fire proceed very slowly unless the fuel is heated to hundreds of degrees Celsius. Common ignition sources include cigarettes, matches, and sparks; friction; overheated electrical circuits; welding operations; space heaters; and lightning.

• For a fire to spread, some of the enthalpy from the ignition region must heat unburned material to a temperature at which it can burn. Fire also can spread by the melting and dripping of burning material or by airborne firebrands.

• A fire can be extinguished by cooling, reducing the oxygen supply, separating the fuel and the oxidizer, and decreasing the concentration of the flame-propagating free radicals.

• Fire hazard is the potential for harm from a particular fire scenario. A fire consequence is a specific quantified hazard. Fire risk combines the severity of consequences and the probability that the consequences will occur. There is a sharp increase in the consequences and risk from a fire in a room if it proceeds to flashover.

Key Terms

backdraft Intense flames emanating from a just opened doorway that introduced fresh air to a fire that had been oxygen starved.

fire consequence A specific, quantified fire hazard.

fire hazard A condition with the potential to create harmful consequences under a specified fire scenario.

fire risk The undesired consequences of a fire multiplied by the likelihood of their happening.

fire scenario A specified set of fire conditions, including details of the fire site and its condition, the combustible items, the number and characteristics of the occupants, and anything else that might affect the outcome of the fire.

flashover The often-sudden transition from local burning to almost simultaneous ignition of (nearly) all of the exposed combustibles in a confined area.

glowing A descriptor of smoldering combustion when it is accompanied by visible thermal radiation.

ignition The onset of combustion.
**pyrolysis** The anaerobic or oxidative decomposition of a gas, liquid, or solid into other molecules when heated.

**rollover (flameover)** The stage of a structure fire when fire gases in a room or other enclosed area ignite.

**smoldering (nonflaming combustion)** The slow, low-temperature, flameless combustion of a solid.

**vitiation** The depletion of oxygen and incorporation of the resulting combustion products in air by a fire.

### Challenging Questions

1. When is oxidation not combustion? When is combustion not oxidation?
2. Give three examples of combustion other than fire.
3. Which kinds of materials can undergo smoldering combustion?
4. Name six ways in which a fire can originate.
5. What is the basic mechanism of fire spread?
6. What are the four fundamental ways of extinguishing a fire?
7. Perform the experiment shown in Figure 6-6. A strip of the cardboard from the back of an 8½ in. × 11 in. notepad is a good test subject, and ordinary kitchen tongs can be used to hold the cardboard safely. What is the general concept demonstrated by this test? (Note: Conduct any experiments with fire outside and away from adjacent structures and materials that could ignite. Wear leather gloves and have a pail of water handy.)

### References