

## Chapter 3

# Flammability Hazard of Materials

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Any material capable of burning with a flame is considered flammable.<sup>1</sup> A flame is a stream of the gaseous fuel and oxidizing agent involved in the combustion process that produces heat (including radiant energy and usually visible light, according to NFPA 921, *Guide for Fire and Explosion Investigations*) and combustion products. The most elementary view of flammability is provided by the fire triangle, which indicates that three components, fuel, oxidizing agent, and heat, are necessary to start a fire. However, the fire triangle does not describe all the conditions for a flaming fire because it does not include the chemical chain reactions and reactive molecules in flame gases. Highly reactive molecular species, referred to as free-radicals, must be present in sufficient concentrations to insure the continuation of chemical chain reactions. Otherwise, flames are extinguished. A more complete visual image of flammability is therefore provided by the fire tetrahedron, which recognizes that in order for flames to exist and not be extinguished, uninhibited chain reactions are necessary in addition to fuel (in a gaseous or vapor state), oxidizing agent, and heat. Whereas the fire triangle identifies the conditions necessary to start a fire, the fire tetrahedron recognizes the conditions sufficient for a flaming fire. These conditions include the availability of gaseous fuel or fuel vapors, which can only be generated if there is sufficient heating from external sources or heat feedback from a burning material's own flames.

The flammability hazard posed by a material is really a quantification of the conditions under which copious amounts of fuel vapors capable of supporting uninhibited chemical chain reactions will be generated in typical occupied environments. Quantification of flammability hazard is usually expressed in terms of ease of flaming ignition, damaging heat and product output from flames, and spread of flame to involve new material surfaces or new locations in damaging flame behavior. In addition, the difficulty of extinguishment of the burning material should be included as part of flammability hazard, following Emmons.<sup>2</sup>

Although it may be simple to determine if a material is capable of supporting flaming combustion, measuring or predicting the flammability hazard of a material is a challenging and complex task. The flammability hazard of a material is dependent on many parameters of its fuel content, including the chemical composition and physical properties of the fuel (see [Section 2, Chapter 1](#), "Physics and Chemistry of Fire"), the geometric configuration of the fuel (see [Section 2, Chapter 2](#), "Physics of Fire Configuration") and the products of combustion. Flammability can also be dependent on scenario factors such as ventilation, oxygen concentration, and radiation feedback from the surroundings. There is no single test or simple index for flammability that adequately captures all these fuel parameters and scenario factors. As a result, performance in one type of

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## Key Terms

ASTM, calorimeter, char, corner test, fire test, flame, flame propagation, flame spread, flammability hazard, gasification, heat flux, heat release rate (HRR), heat transfer, ignitability, ignition temperature, ignition time, intumescence, pyrolysis, smoke generation, smoke yield, smoldering, thermal inertia

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flammability test cannot easily be extrapolated to determine performance for a different type of flammability test.

Given the number of parameters that affect the flammability hazard of a material, it is not surprising that there are many standardized test methods for characterizing flammability. The development and acceptance of each test method can easily take a decade of research and validation, resulting in extensive documentation. Standardized fire test methods are used to compare the behavior or response of different materials to a given or limited set of test conditions. These test conditions may, or most likely may not, represent the material's response under actual fire conditions. If data from such test methods are to be used directly for fire safety design or assessment, the test conditions should be compared carefully with the conditions assumed for the design fire scenario or fire conditions of interest. Property data derived from these numerous test methods can also be used in analytical models to predict flammability hazard for a range of actual fire conditions.

This chapter will provide background information and a description of test methods by which the ignitability, heat release rate, flame spread propensity, smoke yield, and extinguishability components of flammability hazard are measured or characterized for solid combustibles. The discussion of flammability test methods is introduced by a review of how solid combustibles may respond to heat flux from flames or other sources, which begins the process of generating fuel vapors.

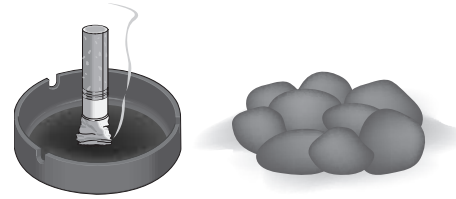
See also Section 2, Chapter 1, “Physics and Chemistry of Fire”; Section 2, Chapter 2, “Physics of Fire Configuration”; Section 2, Chapter 7, “Theory of Fire Extinguishment”; Section 6, Chapter 1, “Fire Hazards of Materials”; Section 6, Chapter 2, “Combustion Products and Their Effects on Life Safety”; and Section 6, Chapter 3, “Concepts and Protocols of Fire Testing.”

## MATERIAL RESPONSE TO INCIDENT HEAT FLUX

When a material is heated, depending on its chemical composition and physical properties, it may respond in a variety of ways. Each of the material responses described below results not only in degradation of the material initially exposed to heat flux but also in life safety and physical damage effects on the surroundings.

### Smoldering

Smoldering is a slow, exothermic surface reaction. Smoldering is usually characterized by glowing, or incandescence, and smoke production (NFPA 921). There is no flaming. Since smoldering is a surface effect it is strongly dependent on environmental conditions in addition to the properties of the fuel and the availability of oxygen. Smoldering is a serious fire hazard for two reasons: (1) it is an inefficient form of combustion so carbon monoxide will form a larger percentage of the combustion products relative to flaming fire conditions,<sup>3</sup> and (2) smoldering provides a means to flaming from heat sources normally too small to generate a flame.<sup>4</sup> Figure 2.3.1 illustrates two examples of smoldering.



**FIGURE 2.3.1** Cigarette and Charcoal/Wood as Examples of Smoldering Combustion

## Pyrolysis and Heat of Gasification

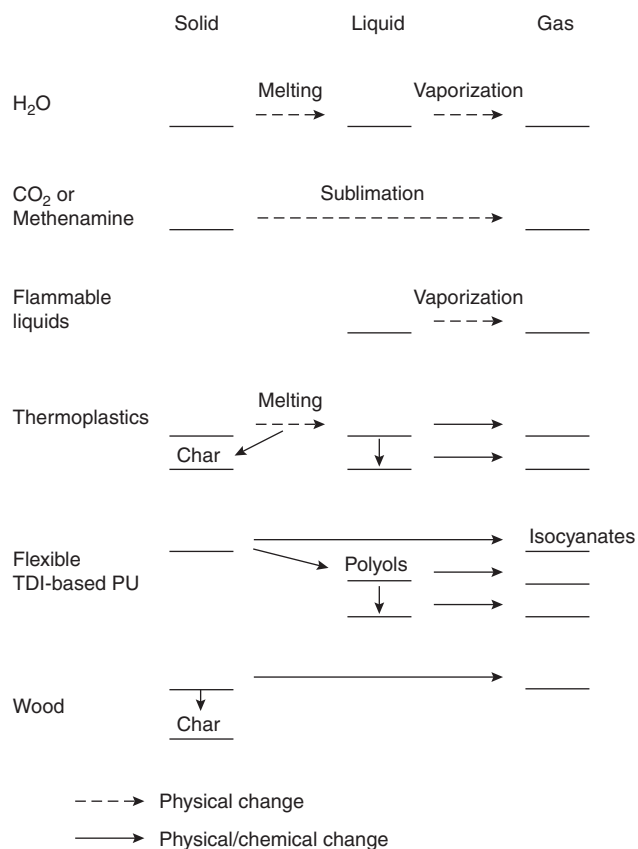
Pyrolysis is the chemical decomposition of a material into one or more other substances due to heat alone (NFPA 921). All solid combustibles must undergo pyrolysis in order to generate gaseous fuel vapors for flaming combustion. The process of converting a solid to gaseous vapors can take many physical paths depending on the chemical composition of the fuel. Cellulosic materials, such as wood, decompose directly to gaseous vapors when heated, leaving behind a residue. Thermoplastics such as polypropylene undergo a two-step pyrolyzation process. As the thermoplastic is heated it melts and turns into a liquid, and then this liquid melt is vaporized into the gaseous fuel. Other materials such as flexible polyurethane foams can decompose by different mechanisms which can produce liquid polyols and gaseous isocyanates<sup>5</sup> (Figure 2.3.2).

The energy required to convert a solid material into a vapor through pyrolysis is termed the *heat of gasification*. This quantity can be obtained from laboratory calorimeters having a controlled atmosphere capability (for example, the Fire Propagation Apparatus<sup>6</sup> described in ASTM E2058, *Standard Test Methods for Measurement of Synthetic Polymer Material Flammability Using a Fire Propagation Apparatus [FPA]*), by substituting pure nitrogen for the air or oxidant normally flowing in the calorimeter and then measuring the mass loss flux from a specimen in nitrogen at different applied heat flux values covering the range expected for real-scale burning objects. In general, the heat of gasification determined from this type of laboratory measurement is not a constant, independent of the heat flux or independent of time during pyrolysis, but for many materials, a representative average heat of gasification can legitimately be defined. The lower the heat of gasification, the greater will be the flammability hazard, since less heat will be required to produce fuel vapor that can react in a flame. As will be discussed later, it is actually the ratio of the heat of combustion to the heat of gasification that is important, since it is the parameter controlling heat release rate and hence, flammability hazard.

## Physical Changes During Pyrolysis

A variety of physical changes result from pyrolysis, including char development, intumescence, melting, and vaporization.

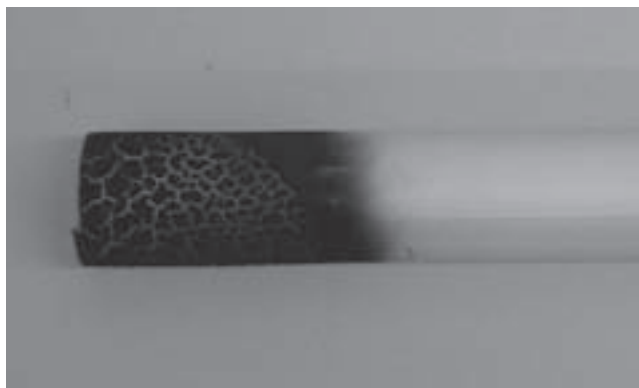
**Char.** Char is a black, carbonaceous, porous residue. The char is a thermal degradation (physical change) of the material being pyrolyzed (chemical decomposition). Organic materials such as wood, wood products, thermoset plastics, and some thermoplas-



**FIGURE 2.3.2** Physical and Chemical Changes During Thermal Decomposition (Courtesy Society of Fire Protection Engineers)

tic polymers form a char layer as they are pyrolyzed. As the char layer develops, it acts as an insulating barrier between the external heat source and the unpyrolyzed fuel under the char. This will slow the pyrolysis rate unless the external heat flux increases to compensate for the insulating char layer.<sup>5</sup> Thermoplastics when exposed to heat tend to soften and melt without forming char. For example, polymethylmethacrylate (PMMA) pyrolyzes with very little melt and leaves no residue. However, rigid polyvinyl chloride (PVC) chars when burned, as do some polyurethane foams.<sup>7,8</sup> Examples of charred wood and a charred thermoset are shown in [Figure 2.3.3](#).

**Intumescence.** Intumescence is defined as the process of swelling up or bubbling up. There are many intumescent coatings on the market for fire protection purposes. These coatings, when heated, increase in volume and decrease in density, simulating the development of a char layer. As the intumescent “char” layer is formed, a blowing agent (a substance used to create bubbles in the material) is released, which creates a low-density, relatively thick carbonaceous layer. Intumescent reactions are typically endothermic due to chemically bound water in hydrates. As the material expands the water is released, maintaining the surface temperature. Once the water has been expended, the remaining “char” layer acts as insulation to the material underneath. The



**FIGURE 2.3.3** Charred Wood and a Charred Thermoset Plastic (Courtesy of National Institute of Standards and Technology)

“char” can expand 50 to 100 times the original thickness of the intumescent coating.<sup>9-12</sup>

**Melting.** When most thermoplastic materials are heated, they melt or soften prior to being vaporized ([Figure 2.3.4](#)). The rate at which melting occurs compared to the burning rate and the melt viscosity, are important for determining the fire hazard.<sup>5</sup> For example, if initial exposure to a heat flux and subsequent burning produces a copious amount of melt having a low viscosity, then there is the potential for extensive fire spread to the surroundings as this melt, possibly supporting flames, comes in contact with new material surfaces. This would be especially dangerous if the melting substance is part of a wall or ceiling lining.

## IGNITABILITY

Ignitability is the ease of initiating self-sustained flaming combustion due to a heat flux exposure. To determine the level of flammability hazard based on ignitability, the primary information needed is the time it takes to ignite the material with a given heat flux exposure. For a given initial heat flux exposure scenario, the greatest flammability hazard results from a material configuration and composition that requires the shortest



**FIGURE 2.3.4** Melted Plastic (Source: Figure 4.11, *User's Manual for NFPA 921*, 2005 edition, courtesy Jones and Bartlett Publishers)

time for ignition. Hence, data on ignitability that gives predicted or estimated ignition times for a variety of heat flux exposures with different fuel configurations and compositions will be most valuable for determining this particular aspect of flammability hazard.

### Ignition Energy and Critical Heat Flux for Ignition

As defined in NFPA 921, the ignition energy of a material is the quantity of heat energy per unit exposed surface area that must be absorbed by the material in order to pyrolyze, ignite, and burn. This energy is the product of the heat flux absorbed by the material and the time of exposure until ignition. A material with a given ignition energy will ignite faster if exposed to a high incident heat flux and slower if the incident heat flux is low. The amount of energy required for ignition also depends on the physical and chemical properties of the material, especially its thermal inertia and ignition temperature. However, the heat flux exposure must be greater than a certain critical value. For a heat flux less than or equal to this value, the ignition time is effectively infinite; i.e., ignition will not occur. This is the definition of the *critical heat flux for ignition*.

### Thermal Inertia

The thermal inertia of a material is the direct product of three physical properties: thermal conductivity ( $k$ ), density ( $\rho$ ), and heat capacity ( $C$ ). Thermal inertia characterizes the rate of surface temperature rise of the material when exposed to heat. Low values of thermal inertia lead to elevated surface temperatures for a given applied heat flux scenario, and hence, to more rapid ignition and a greater flammability hazard if the material is combustible. Although values for thermal conductivity, density, and heat capacity can be found for some materials in the literature, the way that the properties are measured can affect the resulting thermal inertia magnitude. [Table 2.3.1](#) presents data on thermal conductivity, density, and heat capacity for selected materials.

**TABLE 2.3.1** Thermal Properties of Selected Materials

Material	Thermal Conductivity ( $k$ ) (W/m·K)	Density ( $\rho$ ) (kg/m <sup>3</sup> )	Heat Capacity ( $C_p$ ) (J/kg·K)
Copper	387.00	8940	380
Concrete	0.8–1.4	1900–2300	880
Gypsum plaster	0.48	1440	840
Oak	0.17	800	2380
Pine (yellow)	0.14	640	2850
Polyethylene	0.35	940	1900
Polystyrene (rigid)	0.11	1100	1200
Polyvinyl-chloride	0.16	1400	1050
Polyurethane foam*	0.034	20	1400

\*Typical values; properties vary.

$C_p$  = Heat capacity at constant pressure.

Source: Drysdale, D. D., *An Introduction to Fire Dynamics*, 2nd ed., 1999, p. 33. Copyright John Wiley & Sons Limited. Reproduced with permission.

Many materials are not homogeneous in their composition. Therefore they may have varying values for thermal conductivity, density, or heat capacity. Although this may not be a surprise when considering modern composites with visible layers of different materials, it may be surprising to find that wood is not homogeneous. The thermal conductivity of wood is higher in the direction parallel to the grain of the wood. As a result, to ignite the end grain of a piece of wood would require more energy and or more exposure time for a given heat source than to ignite the surface of the wood where the heat flow is perpendicular to the grain.<sup>13</sup> The higher thermal conductivity transfers heat through the wood faster, thereby slowing the storage of heat at the wood surface and increasing the time for reaching the ignition temperature. The thermal conductivity in wood may not only vary with position, but it can also vary with direction at a fixed position. This is an example of a nonisotropic material property.

Further as the wood increases in temperature, the thermal conductivity, density, and specific heat will change due to the evaporation of moisture in the wood. As would be expected, it takes more energy to ignite a piece of wood with higher moisture content.<sup>14</sup> As the wood begins to pyrolyze and a char begins to develop, the physical properties of the wood continue to change. This may also have an impact on the amount of ignition energy required. Hence the assumption that wood, or other materials, behave as inert materials until they ignite is false.<sup>15</sup> These changes are most significant during the ignition process.

Even though there are many variables to consider when assessing the ignitability of a material, average values can still be useful to compare the potential for ignition of two materials. For example, compare the properties given for pine in [Table 2.3.1](#) with those for polyurethane foam. Even though the values for pine may vary during the ignition process, given that the thermal conductivity is more than 4 times that of polyurethane, the density more than 30 times greater, and the heat capacity

is 2 times greater, it is clear that polyurethane cannot transfer heat away from its surface as effectively as wood and therefore would require less ignition energy.

A fire occurred on the night of February 20, 2003, in The Station, a nightclub at 211 Cowesett Avenue, West Warwick, Rhode Island. A band performing that night used pyrotechnics. The sparks from the pyrotechnics ignited polyurethane foam insulation that was installed on the walls and ceiling of the platform being used as a stage. The fire spread quickly along the walls and ceiling area over the dance floor. Smoke was visible in the exit doorways in a little more than one minute, and flames were observed breaking through a portion of the roof in less than five minutes. Egress from the nightclub was hampered by crowding at the main entrance to the building. One hundred people lost their lives in the fire.

In experiments conducted by NIST after the tragedy, birch veneer plywood paneling and ether-based polyurethane foam were exposed to pyrotechnic devices similar to the ones used in the nightclub. The wall-mounted polyurethane foam ignited within 10 seconds. The sparks from the pyrotechnics did not have enough energy to ignite the plywood.<sup>16</sup>

## Ignition Temperature

As defined in NFPA 921, ignition temperature is the minimum temperature a solid material must attain in order to ignite under specific test conditions. Generally, the ignition temperature will be within the range of temperatures at which a material begins to pyrolyze and produce copious vapors, whether by mainly thermal mechanisms controlled by thermal inertia as previously discussed or by chemical bond-breaking processes or a combination of both. The ignition temperature is related to the ignition energy, but it is less fundamental because the manner in which the material is heated, the rate of energy transfer to the material, and the physical and chemical composition of the material affect the ignition temperature. The lower the ignition temperature, the greater the flammability hazard due to ignition.

A review of research literature on the ignition temperature of solid wood shows that the ignition temperature increases as the incident heat flux (energy transfer to the material surface) increases. The ignition temperatures ranges from a minimum of 250°C to initiate smoldering combustion with a low incident heat flux on the order of 5 kW/m<sup>2</sup> to approximately 360°C with a “medium” incident heat flux on the order of 20 kW/m<sup>2</sup> for the piloted ignition of softwoods.<sup>17</sup>

## Ignition Time

Ignition time is the time between the application of an ignition source (usually an imposed heat flux) to a material and the onset of self-sustained flaming either on or near the material. Just as with the ignition energy and the ignition temperature, the time to ignition is also a function of the rate of heat transferred from the ignition source, as well as the physical and chemical properties and geometric configuration of the material. As outlined in previous sections, high incident heat flux, low thermal inertia, and weak chemical bonds will result in faster time to ignition and greater flammability hazard due to ignition.

## IGNITION TEST METHODS

There are many test methods<sup>18</sup> that have been developed to examine the ignitability of a material. Most of these test methods are not quantitative in the sense that a prescribed heat flux is not provided or the test method does not yield quantitative data useful for an engineering prediction of ignition time and hence the ignition aspect of flammability hazard. Although not a standardized test, NFPA 705, *Recommended Practice for a Field Flame Test for Textiles and Films*, is a recommended practice for field flame testing of fabrics and plastic films, to determine their tendency to ignite and sustain burning. It is mentioned here because it is the most basic flammability test, which fire safety professionals can use to determine if further testing is required. The procedure calls for a material sample, at least 12.7 mm × 101.6 mm to be exposed to an open flame from a common wood kitchen match for 12 seconds. The flame should not extend the length of the sample or a distance of 101.6 mm for longer samples. There should not be more than 2 seconds of afterflame on the sample, and materials that break or drip flaming particles on the floor below the sample would fail if the materials continue to burn after reaching the floor. If the test results in the ignition and rapid consumption of the sample, clearly the material is a flammability hazard. On the other hand, if the test results in no ignition, it does not mean that the material complies with applicable fire safety standards. The test results can be affected by environmental conditions, sample size, and flame exposure size. Additional testing is required to quantify the flammability of the material.

The few quantitative test methods that provide data on the ignition aspect of flammability are listed below:

1. Cone calorimeter<sup>19</sup> (NFPA, ASTM and ISO versions; see description later in this chapter), in which a horizontal or vertical 100 mm by 100 mm specimen is exposed to a known heat flux from a conical heater and the time to ignition is measured.
2. Fire propagation apparatus<sup>6</sup> (NFPA and ASTM versions; see description later in this chapter), in which a 100 mm circular horizontal specimen is exposed to a known heat flux from tungsten-quartz heaters and the time to ignition is measured. From data on ignition time at various applied heat flux values, the test method yields the minimum heat flux required for ignition and also the product of the square root of thermal inertia and the excess of ignition temperature above ambient for the test specimen.
3. Lateral ignition and flame spread (LIFT) apparatus<sup>20</sup> (ASTM and ISO versions; see description later in this chapter), in which a vertical 155 mm by 155 mm specimen is exposed to a known average heat flux from a gas-fired radiant panel and the time to ignition is measured. From data on ignition time at various applied heat flux values, the test method contains formulas that yield the minimum heat flux required for ignition and also the ignition temperature and thermal inertia of the test specimen.
4. Intermediate-scale calorimeter (ICAL)<sup>21</sup> (ASTM and ISO versions; see description later in this chapter), in which a 1 m by 1 m vertical specimen is exposed to a known heat flux from a gas-fired radiant panel and the time to ignition is measured

## HEAT RELEASE RATE

Heat release rate is probably the most important quantity used to characterize the flammability hazard represented by a given material. It is a measure of the rate at which a burning item releases chemical energy and is usually expressed as heat released per unit exposed surface area of a burning material or specimen (i.e., kW/m<sup>2</sup>). Used as an input to a computer fire model, the heat release rate can provide information on fire size, fire growth rate, available egress time, and suppression system impact if all the parameters affecting heat release rate are known (see below). The heat release rate of a burning item is the product of mass loss rate (i.e., the mass burning rate) per unit of exposed surface area and its actual (not complete or theoretical) heat of combustion under the conditions of interest. When this heat of combustion is known, the heat release rate can be estimated from the measured mass burning rate. Alternatively, the heat release rate can be determined directly from measurements of the composition of product gases collected in an exhaust hood of a calorimeter. Generally, the greater the heat release rate per unit of exposed surface area of material or per unit floor area of a complex material configuration, the greater is the flammability hazard.

Laboratory calorimeters can provide useful information concerning heat release rate using small material specimens. However, these calorimeters often do not represent the actual performance of a material when used in real life. Laboratory calorimeters do not usually test the same size materials as found in most fire scenarios and the laboratory results can be influenced by the relative closeness of the material edges to the center of the flame zone. There is also little or no geometry consideration included in small-scale tests. Intermediate and large-scale calorimeters attempt to provide a more realistic scenario for testing of materials.

### Parameters Controlling HRR

Although the heat release rate (HRR) of real material configurations can be obtained from full-scale tests (see discussion below), it is impractical to test materials in every possible configuration and fire scenario (e.g., within enclosed spaces of different sizes or in different warehouse storage arrangements) to determine the flammability hazard due to heat release rate. For this reason, materials are often tested in a reference fire scenario, such as a room test or a corner test or a commodity evaluation test having one or two geometric scales that are characteristic of a wide range of practical situations. Even these full-scale reference tests can be expensive, so predictions of flammability hazard due to heat release rate that are based solely on laboratory property measurements would be highly desirable. For this to be done, the parameters controlling heat release rate must be identified and then characterized by practical test methods.

Similar to the case for ignition, the net heat flux absorbed by a material and the heat of gasification of a material determine the mass loss flux of fuel vapors from a burning material surface. Here, the net heat flux is the heat flux absorbed from a material's own flames and from any heat source surrounding the burning material (e.g., from other burning objects, from a hot gas layer in an enclosure, or from heated enclosure surfaces)

minus any heat losses from a material's own pyrolyzing hot char or melt layer (such as the glow of wood char in a fireplace). In the simple situation of a constant net heat flux and constant heat of gasification, it is the ratio of net heat flux to heat of gasification that yields the fuel mass loss flux. As noted above, the product of the mass loss flux and the relevant heat of combustion then yields the heat release rate of the burning material. Hence, it is the ratio of the heat of combustion to the heat of gasification, together with the net absorbed heat flux, that determines the heat release rate. The greater the magnitude of this ratio, which has been called the heat release parameter (HRP) by Tewarson,<sup>22</sup> the greater is the flammability hazard. HRP can often be measured directly in a laboratory calorimeter if there is a linear dependence of heat release rate on the applied heat flux to a material specimen over a range of applied heat flux and material thermal thickness estimated to cover the fire scenarios of interest. If such is the case, HRP is simply the slope of the linear relationship. Otherwise, the heat of combustion and heat of gasification can be measured individually in a calorimeter, the former as the ratio of total heat released to total mass lost and the latter from mass loss data at several precisely known imposed heat fluxes in a nitrogen environment.<sup>6</sup>

Tabulation of HRP values<sup>22</sup> shows that materials known to have a very low flammability hazard typically exhibit an HRP approaching unity while more hazardous materials have an HRP greater than 10. Alpert<sup>23</sup> has developed an algebraic model utilizing HRP values obtained from heat of gasification tests in nitrogen together with flame heat flux values determined from calorimeter data on smoke yield (discussed in the next section). This algebraic model predicts both heat release rates and the propensity for fire propagation in a parallel panel configuration, thus yielding a prediction of flammability hazard (see Parallel Panel Test later in this chapter). Nam<sup>24</sup> has extended and perfected this parallel panel model.

### Flame Heat Transfer

In any prediction of heat release rate and hence flammability hazard, the heat flux from the flame of a burning material is critical, as explained above. If heat release rate is not being measured in a full-scale fire scenario by a large-capacity calorimeter, then flame heat transfer must be simulated in a laboratory calorimeter by using electrical or gas-fired radiant heating elements in the calorimeter apparatus. Obviously, the heat release rate measured in the apparatus will be determined by the choice of the imposed heat flux. To avoid the problem of choosing an imposed heat flux that accurately simulates full-scale flames, the heat release rates of many material specimens are often compared by testing at the same imposed heat flux selected to be representative of what would be expected in typical fire scenarios. However, materials having flames with a higher flame heat transfer than simulated in the apparatus would presumably have a higher flammability hazard and those with lower flame heat transfer a lesser hazard. Typically, materials are tested in laboratory calorimeters at an imposed heat flux of 50 to 75 kW/m<sup>2</sup>, which is a flux known to occur in many types of real scale fires. Under such conditions, measured heat release rates less than 50 to 100 kW/m<sup>2</sup> often indicate a relatively low flammability hazard.

The heat transfer from real-scale flames is primarily due to thermal radiation, which, as discussed in Section 2, Chapter 1, “Physics and Chemistry of Fire,” depends both on flame temperature and flame emissivity primarily determined by soot concentration profiles within the flame. The configuration of the burning material will also affect flame heat transfer, as discussed in Section 2, Chapter 2, “Physics of Fire Configuration.” Significant progress is being made to understand flame heat transfer through the development of empirical correlations (e.g., in room-corner configurations<sup>25</sup> and in parallel panel configurations<sup>25</sup>) guided by simplified models.<sup>26</sup> These correlations show that the smoke yield of the flame for a burning material specimen, as obtained in a laboratory apparatus, is a critical determinant of flame heat transfer levels. Generally, higher smoke yields imply sootier flames with higher flame heat transfer and a greater flammability hazard. Note that at a sufficiently high smoke yield, combustion efficiency, or the actual heat of combustion, will be reduced to such an extent that heat release rates (and hence the flammability hazard) are reduced in spite of enhanced flame heat transfer.

## HRR TEST METHODS

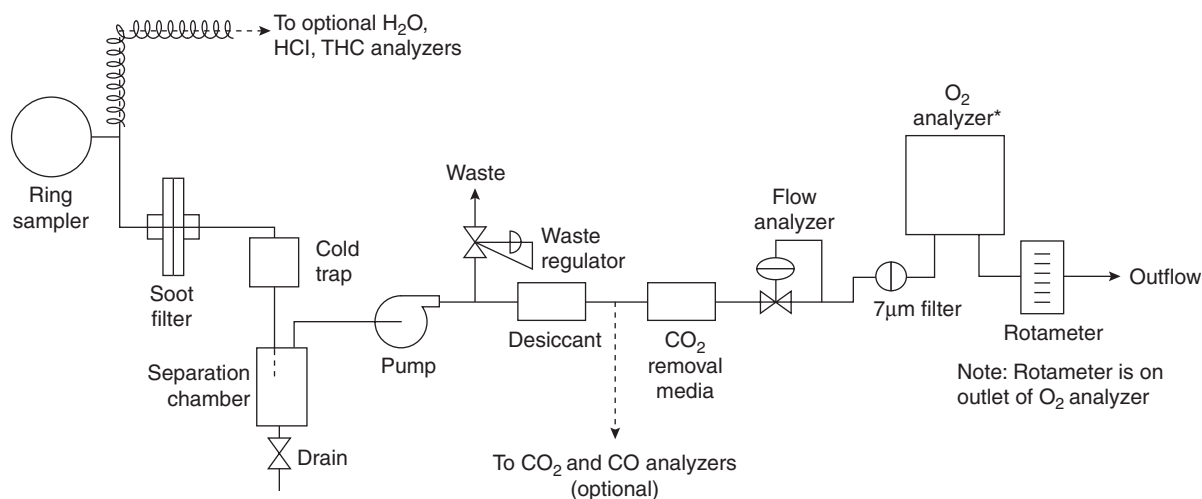
The heat release rate of actual material configurations can be measured in large-scale calorimeters, some of which are capable of safely handling tens of megawatts. In that case, the measured heat release rate (either peak or average values) can be used directly to estimate flammability hazard. Otherwise, laboratory-scale calorimeters must be used to obtain quantitative data from material specimens ranging in size from 100 mm up to 1 m across.

### Measurement of Heat Release Rate

The oxygen consumption method has been identified as the most accurate means for determining heat release rate. This technique

was refined in the late 1970s and early 1980s by researchers at the National Bureau of Standards. Using the principle of oxygen consumption, it is possible to calculate the heat release rate of burning materials when the products of combustion are collected in an exhaust hood. Thornton<sup>27</sup> found in 1917 that many organic materials produced almost the same amount of heat per unit mass of oxygen consumed. Hinkley et al.<sup>28</sup> suggested using oxygen concentration in exhaust gases to determine the heat release rate of wood cribs in 1968. Parker<sup>29</sup> used this technique to determine the heat release rate of specimens in the ASTM E84, *Standard Test Method for Surface Burning Characteristics of Building Materials*, tunnel test. Huggett<sup>30</sup> calculated an average value for the heat release from a fire involving typical organic fuels to be 13.1 MJ per kilogram of oxygen consumed. However, for materials with very low heat release rates (e.g., below 100 kW/m<sup>2</sup>) or very sooty flames, comparable or greater accuracy can be obtained by measuring the generation rate of product gases such as carbon dioxide and carbon monoxide, as long as the elemental composition of the material specimen is known (or measured by readily available and inexpensive laboratory techniques).<sup>31</sup>

The calculation of heat release rate of fires burning in normal air, whether using oxygen consumption or product gas generation, requires a minimum of two measurements, the flow rate of the products of combustion through the exhaust system and product gas concentration in the exhaust products. Parker<sup>32</sup> presents several sets of equations for calculating heat release rate using oxygen consumption. The appropriateness of each set of equations depends on the combustion products being measured.<sup>31</sup> A paper by Janssens<sup>33</sup> proposes a form of the equations for calculating heat release rate specifically for full-scale fire test applications. These equations use mass flow rates instead of volumetric flow rates. Volumetric flow rates can lead to confusion because of the need to choose an arbitrary reference temperature and pressure. Figure 2.3.5 shows a schematic of a sampling system for measuring heat release rates.



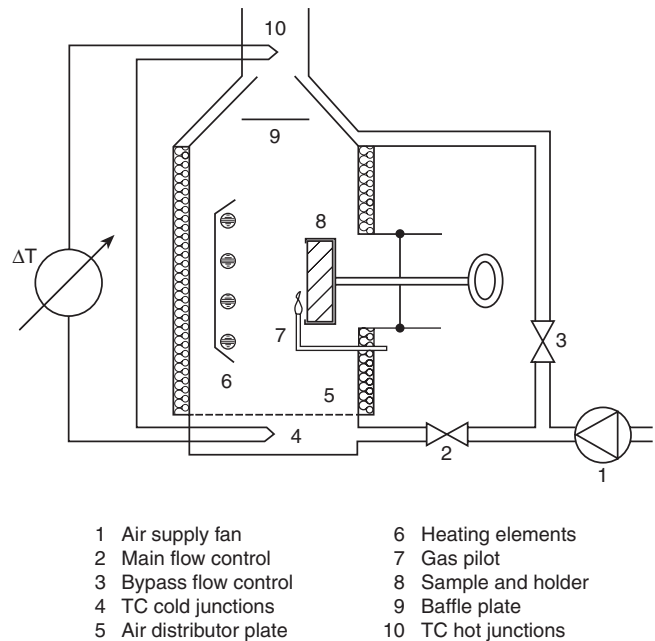
**FIGURE 2.3.5** Schematic of Sampling System for Measuring Heat Release Rates from Burning Items. \*To include absolute-pressure transducer. (Source: National Institute of Standards and Technology)

## Laboratory-Scale Calorimeters

Early calorimeters functioned by measuring the temperature increase in the exhaust stream resulting from the combustion of a flammable item.<sup>34</sup> Developed in 1959, the FM Global Construction Materials calorimeter is probably the earliest example of a device designed to measure heat release rate using the potentially very accurate substitution principle.<sup>35</sup> The test specimen, approximately 1.22 m by 1.22 m and oriented face-down, was exposed to an oil burner fire. A second test would be conducted with a noncombustible blank exposed to the oil burner flames while auxiliary propane gas burners were adjusted to reproduce the measured exhaust gas temperature increase. The energy release rate from the propane burners would correspond to (or “substitute for”) the energy release rate of the test specimen. This device was considered cumbersome, requiring two tests for each specimen and did not see widespread use. Subsequently, a similar calorimeter using a 0.46 m by 0.46 m sample mounted vertically was built by the U.S. Forest Products Laboratory.<sup>36</sup>

The National Bureau of Standards NBS-I calorimeter improved upon earlier calorimeter designs with the addition of a feedback loop.<sup>37</sup> As the specimen burned, the system would reduce the quantity of propane being added to the system, thus keeping the energy in the system constant. The energy release accounted for by the reduced propane flow would represent the heat release rate of the flammable item. The NBS-I could expose vertically oriented samples 114 mm by 152 mm and up to 25 mm thick to a maximum heat flux of 100 kW/m<sup>2</sup> for short durations. Although this system eliminated some of the early problems, its complexity, sensitivity to exhaust pressure fluctuations, and long equilibrium times limited its widespread use. The NBS-I inspired the development of a similar calorimeter at Stanford Research Institute with a maximum heat release rate measurement capability of 120 kW/m<sup>2</sup>.<sup>38</sup>

**OSU Apparatus.** The Ohio State University (OSU) calorimeter, designed by E. E. Smith, is one of the most widely used bench-scale calorimeters.<sup>39</sup> Unlike many other bench-scale calorimeters that functioned by adding or substituting an energy source, this calorimeter operated by measuring the temperatures of the incoming air and the exhaust gases while the sample burns in an insulated box. This method of operation was referred to as the “sensible enthalpy rise method.” Although attempts were made to limit heat losses, it was impossible to totally eliminate them. Therefore, calibration runs using a gas burner were still necessary to develop a correlation between heat release rate and exhaust gas temperature. Using radiant heaters, vertically oriented specimens, up to 0.15 m by 0.15 m, could be exposed to a peak heat flux of 65 kW/m<sup>2</sup>. Sample size was limited to 0.11 m by 0.15 m and a peak heat flux of 50 kW/m<sup>2</sup> when tested horizontally using an aluminum reflector. The OSU calorimeter was adopted as ASTM E906, *Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products*, in 1983.<sup>40</sup> Although the ASTM standard test method has changed little since its adoption, a number of researchers have modified the OSU calorimeter for oxygen consumption measurements. Figure 2.3.6 illustrates the OSU calorimeter.



**FIGURE 2.3.6** Schematic of the OSU Apparatus (Courtesy Society of Fire Protection Engineers)

**Fire Propagation Apparatus.** At FM Global in 1975, Tewarson first described a small-scale flammability apparatus for measuring heat release rate.<sup>41</sup> The convective component of the total heat release rate was obtained from measurements of the enthalpy of the exhaust stream. The total heat release rate was calculated from the specimen mass loss rate, oxygen bomb heat of combustion, and the generation rates of carbon dioxide and carbon monoxide. Alternative calculations using oxygen consumption or carbon dioxide and carbon monoxide generation in lieu of oxygen bomb measurements were also implemented. Test specimens, up to 100 mm in diameter and 50 mm thick, could be exposed to a peak heat flux of 65 kW/m<sup>2</sup> using tungsten/quartz heaters. A larger version of this calorimeter was implemented as the intermediate-scale flammability apparatus with a capability to expose samples up to 305 mm in diameter and 75 mm thick. The intermediate-scale apparatus could test items with heat release rates up to 500 kW, whereas the small-scale apparatus was limited to peak heat release rate measurements of 10 kW. In 2000, test methods based on the small-scale apparatus were adopted as ASTM E2058, *Standard Test Methods for Measurement of Synthetic Polymer Material Flammability Using a Fire Propagation Apparatus (FPA)*.<sup>6</sup> In 2001, test methods based on the same apparatus with smoke and corrosion measurement capabilities added to characterize the hazards of materials in commercial cleanrooms were adopted as NFPA 287, *Standard Test Methods for Measurement of Flammability of Materials in Cleanrooms Using a Fire Propagation Apparatus (FPA)*. Figure 2.3.7 illustrates the Tewarson fire propagation test apparatus. Figure 2.3.8 illustrates the ASTM E2058 apparatus.

**Cone Calorimeter.** The cone calorimeter is probably the most versatile oxygen consumption method for measuring heat re-





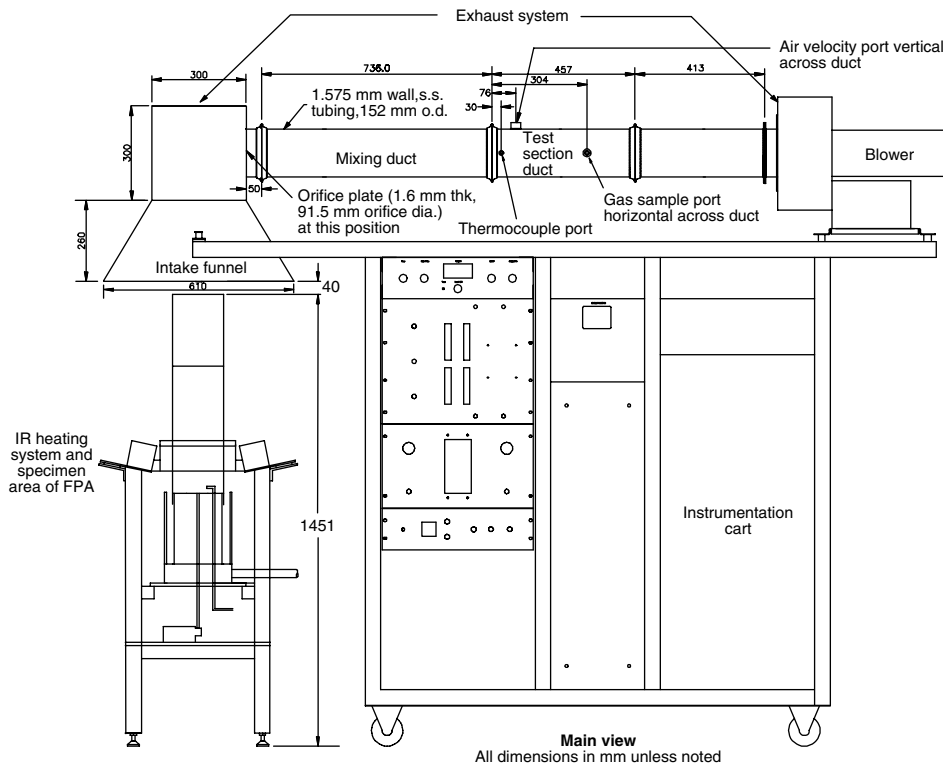
**FIGURE 2.3.7** Quartz Heaters and Controlled Combustion Environment of the Fire Propagation Apparatus (Courtesy Ronald Alpert)

lease rate. It was developed at NIST in the 1980s<sup>42</sup> and is presently the most commonly used bench-scale rate of heat release apparatus.<sup>43</sup> The cone calorimeter has been adopted as ASTM E1354, *Test Method for Heat and Visible Smoke Release Rates*

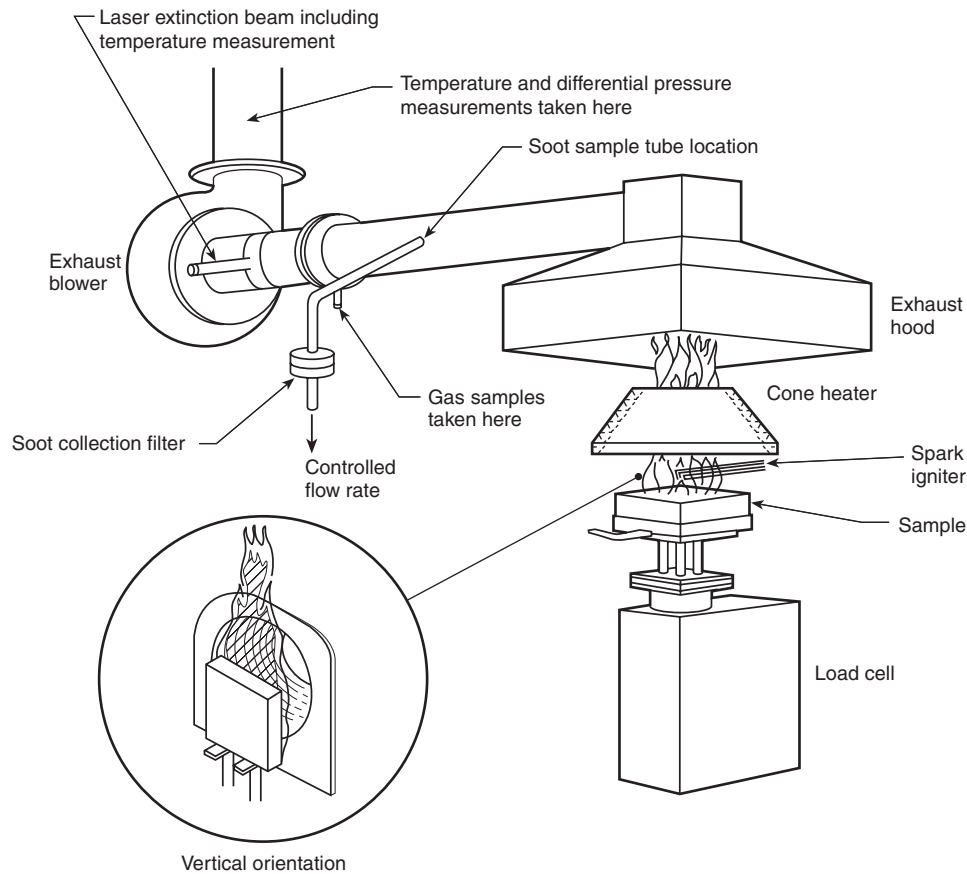
for Materials and Products Using an Oxygen Consumption Calorimeter.<sup>19</sup> It has also been adopted by the National Fire Protection Association in NFPA 271, *Standard Method of Test for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*, and as an international standard, ISO 5660-1.<sup>44</sup>

The cone calorimeter consists of a heater, spark ignitor, sample holder, and load cell located underneath an exhaust hood. Typically, the sample is located in the open with free access of air to the combustion zone. The heater consists of a 5 kW electrical heating element inside an insulated stainless-steel conical shell. Samples can be tested in either a horizontal or vertical orientation. When tests are performed in the horizontal configuration, the specimen is positioned approximately 25 mm beneath the bottom plate of the cone heater. Flames and products of combustion pass through a circular opening at the top of the heater. The heater can expose samples to a maximum irradiance of approximately 100 kW/m<sup>2</sup>. Figure 2.3.9 is a schematic of the cone calorimeter.

For piloted ignition tests, an electric spark ignitor is positioned at the top of vertical samples and over the center of horizontal samples. Samples are typically 100 mm by 100 mm, and they can be wrapped with aluminum foil to minimize edge effects. Combustion products and dilution air are extracted through the hood and exhaust duct by a high temperature fan. The flow rate can be adjusted between 0.01 and 0.03 m<sup>3</sup>/sec.



**FIGURE 2.3.8** ASTM E2058 Apparatus (Source: Reprinted, with permission, from ASTM E2058, *Standard Test Methods for Measurement of Synthetic Polymer Material Flammability Using a Fire Propagation Apparatus (FPA)*, Annex A1, copyright ASTM International, W. Conshohocken, PA)



**FIGURE 2.3.9** Schematic View of the Cone Calorimeter (Courtesy Society of Fire Protection Engineers)

The volumetric flow rate is kept constant during testing. The sample is mounted on a load cell to determine mass loss rate during a test, and smoke obscuration is measured using a laser light source. The gas flow rate in the exhaust duct is calculated from the pressure drop across and temperature at an orifice plate in the duct. Finally, the concentrations of oxygen, carbon dioxide, carbon monoxide, and other gases are measured using appropriate instruments. Heat release rate is calculated from the gas concentration and mass flow measurements.

**Single Burning Item Test.** The single burning item test method, or EN 13823, is a CEN (European) standard<sup>45</sup> with the objective of reproducing the transient heat release rate results from the full-scale ISO 9705 room-corner test (discussed later). Two heat release parameters are measured: the ratio of the peak heat release rate to the time at which this peak HRR occurs, or the fire grow rate (FIGRA) index, and the total heat release over the first 600 seconds of the test (THR600). Whether this 1.5-m-high corner test accomplishes the stated objective is definitely open to question since the 31 kW heat release rate of the initiating propane flames from a triangular gas burner produces a rather small incident heat flux on the test specimen. In particular, test specimens consisting of sandwich panels with a combustible insulating core and a metal covering have not yielded the same

result in the EN 13823 test as in the ISO 9705 room since the exposure heat flux has not been sufficient to penetrate the metal cover.

### Large-Scale Calorimeters

The oxygen consumption technique has been successfully implemented in a number of intermediate and large-scale calorimeters. These large-scale calorimeters have been developed to measure heat release rate from an assortment of different flammable items. These items range from single pieces of furniture, such as couches or mattresses, to entire rooms. Typically, the item or items of interest are burned under a large collection hood or in a room vented to this large hood. The hood would be instrumented to measure the temperature and velocity of the exhaust gases. In addition, the concentrations of oxygen, carbon dioxide, and carbon monoxide would also be measured during the experiments. Burning materials inside a room enclosure has the advantage of including the impact of the room; however, the potential lack of oxygen in the room would prevent the complete combustion of the items of interest. The calorimeter would be unable to distinguish between burning of the object in the room and burning of the gases outside of the room. Measuring the heat release rate from an item burning in the open with excess

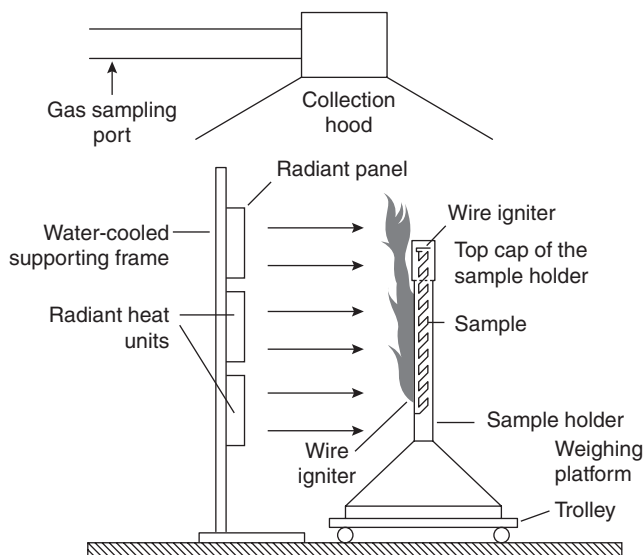
oxygen would allow for complete combustion and a better measure of the item's total heat release rate.

**Room-Corner Fire Test for Surface Linings.** Several standard room fire tests have been developed. A room calorimeter developed at Monsanto Chemical was one of the earliest attempts to build a room-size calorimeter.<sup>46</sup> This test used exhaust gas temperature measurements and statistical analysis to determine heat release rate in lieu of oxygen consumption calorimetry. The American Society for Testing and Materials developed a standard room fire test in the early 1980s,<sup>47</sup> which was standardized in 2003 as ASTM E2257, *Standard Test Method for Room Fire Test of Wall and Ceiling Materials and Assemblies*.<sup>48</sup> The ASTM room measures 2.4 m by 3.7 m in size and is 2.4 m high. The room has a single doorway in one wall measuring 0.76 m wide by 2.03 m high. A standard guide, ASTM E603, *Standard Guide for Room Fire Experiments*, for conducting and instrumenting room fire tests<sup>49</sup> is also available. Many years ago, the work on room fire tests in ASTM inspired the ISO 9705 standard<sup>50</sup> that has been designated in Europe as a reference fire scenario for the evaluation of surface lining flammability hazard. NFPA 286, *Standard Methods of Fire Tests for Evaluating Contribution of Wall and Ceiling Interior Finish to Room Fire Growth*, is a slightly different version of this ISO standard. Another room fire test was developed for use as a potential standard room fire test by NORDTEST.<sup>51</sup>

**Furniture Calorimeters.** A number of open calorimeters have been developed by various research organizations throughout the world. One of the first was the NBS Furniture Calorimeter.<sup>52</sup> This device used oxygen consumption to determine heat release rate. In addition, mass loss, smoke concentration, and heat flux were measured during combustion of the sample. Other open calorimeters have been developed by NORDTEST,<sup>53</sup> Underwriters Laboratories,<sup>54</sup> FM Global Research,<sup>55</sup> and Statens Provningsanstalt.<sup>56</sup>

**ICAL.** The ICAL is an intermediate-scale calorimeter that has been designed to measure heat release rate, mass loss rates, and visible smoke development from a 1 m × 1 m vertically oriented, nonmelting material under well-ventilated conditions. The test sample is exposed to a uniform heat flux up to 50 kW/m<sup>2</sup> from a gas-fired radiant panel. This device is documented in ASTM E1623, *Test Method for Determination of Fire and Thermal Parameters of Materials, Products and Systems Using an Intermediate Scale Calorimeter (ICAL)*<sup>21</sup> as well as in ISO 14696.<sup>57</sup> Figure 2.3.10 illustrates the ICAL calorimeter.

**Commodity Fire Tests.** Several test methods have been developed for measuring the heat release rate from various commodities in specific arrangements. Standards exist for testing stacked chairs,<sup>58</sup> upholstered chairs,<sup>59</sup> and mattresses<sup>60</sup> in open calorimeters as well as in room enclosures while test methods have been established in the United States and Europe to determine the extinguishability of commodity array segments using an applied water droplet flux during the measurement of heat release rate by collecting combustion products in an exhaust hood (see Section 2, Chapter 7, “Theory of Fire Extinguishment”).



**FIGURE 2.3.10** Intermediate-Scale Calorimeter (ICAL) (Source: Reprinted, with permission, from ASTM E1623, *Standard Test Method for Determination of Fire and Thermal Parameters of Materials, Products, and Systems Using an Intermediate Scale Calorimeter (ICAL)*, copyright ASTM International, W. Conshohocken, PA)

Certain interior finish materials are tested in a room-corner arrangement, described in NFPA 265, *Standard Methods of Fire Tests for Evaluating Room Fire Growth Contribution of Textile Coverings on Full Height Panels and Walls*, and NFPA 286. The heat release rate data obtained from these larger calorimeters can be used as an estimate of the hazard potential from the respective item. In the United States, several of the nongovernmental fire test laboratories—FM Global, Underwriters Laboratories, and Southwest Research Institute—have increased the size of their large scale calorimetry labs in order to accommodate larger commodity fire testing.

## FLAME PROPAGATION PROPENSITY

Another important parameter for determining the flammability hazard of an item is its propensity to support flame spread. The buoyancy flow induced by a fire and natural wind flow can aid the spread of flames or hinder it. When the flames spread in the direction of the fire-induced flow or with the wind, it is termed “wind-aided” spread (e.g., flame spread up a vertical surface, as discussed in Section 2, Chapter 2, “Physics of Fire Configuration”). “Opposed-flow” flame spread occurs when the flame motion is opposite the direction of fire-induced air flow or into the wind<sup>61</sup> (e.g., flame spread down or laterally on a vertical surface and flame spread over a horizontal surface, as discussed in Section 2, Chapter 2, “Physics of Fire Configuration”). The flame spread across the surface of a solid material is characterized by two moving boundaries or fronts. The front where visible flaming occurs in the gas phase and a pyrolysis region moving through the solid phase within the flame front. The

velocity of this flame front and the associated pyrolysis front can be useful for determining fire hazard, especially in the case of opposed-flow flame spread where such velocities are easily measured. However, in the case presenting the greatest danger, namely wind-aided or upward flame spread, it may be equally important to determine whether or not a material configuration and fire scenario will lead directly to self-sustained flame spread, which could result in rapid movement of the flame and pyrolysis front over the entire upward extent of the material surface. Obviously, the greater the velocity and/or extent of flame spread on a material, the greater the flammability hazard.

Upward or wind-aided flame spread propensity or velocity on a single vertical surface can be used to characterize flammability hazard in test methods. However, conclusions in this case may be incorrect because radiant heat losses from charring materials can prevent flame spread altogether whereas spread velocities for noncharring, nonmelting materials may be very high and not very reproducible. Lateral, downward, or opposed-flow flame spread velocity and the extent of flame spread on surfaces can also be used in test methods to characterize flammability hazard. The disadvantage with test methods involving opposed-flow flame spread is that such configurations are not sensitive to flame radiant heat transfer and hence may not correctly predict flammability hazards in realistic configurations and sizes. Tests involving wind-aided (upward) flame spread propensity in a parallel panel configuration, by eliminating much of the radiant heat losses, have provided useful measures of flammability hazard for materials ranging from wood to highly fire-resistant, engineered polymers. In addition, the propensity for limited (a steady flame front) or unlimited (an accelerating flame front moving upward) flame spread in the parallel panel configuration has been modeled successfully.<sup>23,24</sup>

## FLAME SPREAD TEST METHODS

### Tunnel Test

The Steiner tunnel test is one of the earliest test methods developed for assessing the flammability hazard of materials through measurement of flame spread. This test, ASTM E84,<sup>62</sup> provides a normalized flame spread rating for materials mounted on the ceiling of the test apparatus under forced-flow conditions. A test specimen 7.6 m long and 1.67 m wide is mounted on the ceiling of a tunnel measuring 8.7 m long by 0.45 m wide and 0.31 m high. The sample is exposed at one end to a 79 kW gas burner with a forced draft through the tunnel of 1.2 m/sec. Relative indexes of flame spread and smoke developed are determined from measurements obtained during the 10 minute test. The test materials are compared to test performance of inorganic cement board and red oak flooring, which have flame spread indexes of 0 and 100 respectively. While the values obtained from this apparatus have been used for regulatory purposes over the last several decades, its relationship to real-world applications has not been established. The requirement to mount a test specimen on the ceiling, its limited ability to test materials that melt and drip, and the limited ventilation available for some polymer foams that produce high volumes of pyrolysis and combustion products are some of the limitations of this apparatus. This test

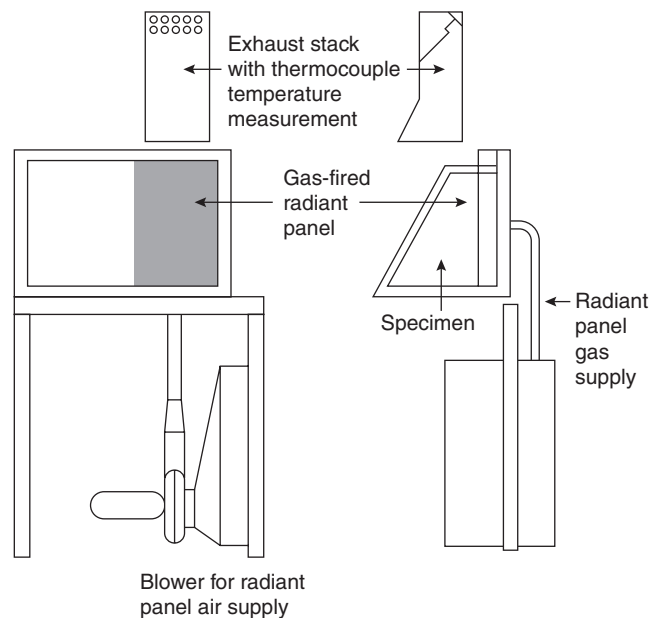
is also documented in NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials*.

### Radiant Panel Test

Unlike the tunnel test, which is considered a wind-aided flame spread configuration, the radiant panel test provides a measure of downward, opposed-flow flame spread.<sup>63</sup> This test method has also been used extensively in building codes for regulatory purposes. The apparatus measures the surface flammability of materials using a gas-fired radiant panel. A specimen approximately 152 mm × 457 mm is exposed to a radiant panel that is 305 mm × 457 mm. The specimen is sloped away from the panel at a 30° angle with the top of the specimen being closest to the panel. The slope provides a decreasing heat flux along the specimen. A relative index of flame spread is calculated based on the distance the sample burns. This test method is referenced for building products as ASTM E162, *Standard Test Method for Surface Flammability of Materials using a Radiant Energy Source*<sup>64</sup> and for cellular plastics as ASTM D3675, *Standard Test Method for Surface Burning Characteristics of Building Materials*.<sup>65</sup> Figure 2.3.11 illustrates the radiant panel test apparatus.

### LIFT Apparatus

Another test apparatus to measure opposed-flow flame spread is referenced in ASTM E 1321, *Standard Test Method for Determining Material Ignition and Flame Spread Properties*.<sup>20</sup> This apparatus, often referred to as the lateral ignition and flame spread test (LIFT), uses a gas-fired radiant panel to measure surface ignition and lateral spread of flames on materials under opposed-flow conditions. The radiant panel is installed at a 15 degree angle to



**FIGURE 2.3.11** Radiant Panel Test Apparatus from ASTM E162 (Source: National Institute of Standards and Technology)

the test specimen and can provide up to 65 kW/m<sup>2</sup> of heat flux at the 50 mm position. The sample size is 155 mm by 800 mm. A modified version of the test with a different sample orientation is identified as the horizontal ignition and flame spread test (HIFT). Unlike many older test methods, this apparatus provides information in engineering terms. Data obtained from these tests (LIFT and HIFT) allow the flame spread velocity and external heat flux required for flame spread to be determined. The resulting information can be used to evaluate the potential opposed-flow flame spread flammability hazard of many different materials. The LIFT apparatus is also used to examine the flammability of marine surface finishes, and ASTM E1317, *Standard Test Method for Flammability of Marine Surface Finishes*, governs its use for maritime applications.<sup>66</sup> ISO 5658-2<sup>67</sup> is a version of the apparatus nearly identical to ASTM E1321.

### Radiant Panel Flooring Test

As a result of some major fires where flame spread on carpeting was a major factor, a radiant panel flooring test was developed at NBS. This test method was adopted as ASTM E648, *Standard Method of Test for Critical Radiant Flux of Floor-Covering Systems Using a Radiant Heat Energy Source*<sup>68</sup> or NFPA 253, *Standard Method of Test for Critical Radiant Flux of Floor Covering Systems Using a Radiant Heat Energy Source*. A 1 m long test specimen is mounted horizontally beneath an air-gas-fueled radiant panel. The panel is inclined at 30°, providing a heat flux on the test specimen varying from 10 kW/m<sup>2</sup> at the point closest to the panel to 1 kW/m<sup>2</sup> at the farthest point. The critical radiant flux corresponds to the flux at the point of maximum flame propagation. This parameter can also be used in engineering analysis of fire performance of materials. A similar test designed to evaluate attic insulation is referenced in standard ASTM E970, *Standard Test Method for Critical Radiant Flux of Exposed Attic Floor Insulation Using a Radiant Heat Energy Source*.<sup>69</sup>

### Vertical Burn Test

The UL 94 vertical burn test provides a measure of a thin material's resistance to self-sustained ignition in an upward flame spread configuration.<sup>70</sup> This test method can be used to select materials for use in electronic devices or appliances. A standard laboratory Bunsen burner (ASTM D5025, *Specification for a Laboratory Burner Used for Small-Scale Burning Tests on Plastic Materials*, burner at 105 mL/min flow rate)<sup>71</sup> is used to produce a 50 W premixed methane-air flame for the ignition source. The flame is applied for 10 seconds and is intended to simulate a short duration ignition such as from an electrical short. The test method utilizes a sample 125 mm long and 13 mm wide mounted 30 cm above a piece of loose cotton. The tested material receives a V-rated classification based on the results from a set of five tests. If the material fails to meet any of the criteria, a V-fail or V-not rating is assigned. The V-ratings are summarized below.

#### V-0 Classification

1. The afterflame time for each individual specimen is less than 10 seconds.

2. The total afterflame time for any condition set is less than 50 seconds.
3. The cotton indicator is not ignited by flaming particles or drops.

#### V-1 Classification

1. The afterflame time for each individual specimen is less than 30 seconds.
2. The total afterflame time for any condition set is less than 250 seconds.
3. The cotton indicator is not ignited by flaming particles or drops.

#### V-2 Classification

1. The afterflame time for each individual specimen is less than 30 seconds.
2. The total afterflame time for any condition set is less than 250 seconds.
3. The cotton indicator is ignited by flaming particles or drops.

An important caveat associated with this test method is that even the V-0 classification does not ensure the material will not spread flames in real fire scenarios. (The 50 W [not 50 kW] exposure flame is meant to reproduce a very small ignition source. The danger of course is that someone not knowledgeable about flammability hazards will misinterpret the applicability of these ratings.)

### Parallel Panel Test

A parallel panel apparatus for evaluating the fire propagation hazard of exposed polymer materials was developed at FM Global Research in the 1970s. This parallel panel configuration has most often been used to determine if polymeric materials represent a flammability hazard when installed in wall linings and equipment in highly sensitive commercial fabrication areas where even a small fire cannot be tolerated, such as a cleanroom in a fabrication facility. The apparatus, which now qualifies materials for use in commercial semiconductor clean rooms<sup>72</sup> following the ANSI FM 4910 protocol,<sup>73</sup> consists of two parallel 2.4 m high × 0.6 m wide panels separated by a 0.3 m × 0.6 m horizontal sand burner. Each panel is faced with a test specimen attached to a 25 mm thick sheet of calcium silicate board, which, in turn, is attached to a 13 mm thick sheet of plywood. The test specimen panels are exposed to the sand burner flames for 20 minutes only after the burner has reached a steady heat release rate of 60 kW. During the test, the total heat release rate and smoke generation rate of the panel assembly are obtained from gas and soot concentration measurements in an exhaust hood, the mass loss rate of the assembly is obtained from load transducer measurements, panel flame heat flux is obtained from imbedded gauges and video observations are recorded of flame front position beyond the 0.6 m height of the exposure flames. All of these measurements are used to determine the flammability hazard of the panel specimen in a specific fire scenario. This test is sufficiently large that, as in most dangerous fires, flame radiation is dominant. There is also ample air access and confinement of heat so that the test is rigorous and realistic.

The relatively simple test geometry both increases the likelihood of modeling success and provides access to instrumentation. Yet the surface area of the material specimen required is small enough to make testing economical.

The parallel panel configuration and sand burner has also been used with double height panels (4.88 m high instead of the usual 2.44 m) to evaluate flame spread on polymer insulated cables in a simulated vertical cable tray configuration, which provided the technical basis for the FM 3972 cable standard.<sup>74</sup> Results from this larger configuration when there is negligible flame spread beyond the exposure fire are in excellent agreement with the UL 910/NFPA 262, *Standard Method of Test for Flame Travel and Smoke of Wires and Cables for Use in Air-Handling Spaces*, plenum cable test based on the ASTM E84 tunnel apparatus. Research on the parallel panel configuration now in progress<sup>24</sup> has shown that by increasing the scale of the panels and the heat release rate of the sand burner, it is very likely that a correlation can be obtained with flame spread results in very large-scale corner tests (see below).

### Large-Scale Corner, Room and Façade Tests

There are several large-scale test methods<sup>75–78</sup> that expose wall and ceiling lining materials (in many cases, only sandwich-type panels of metal covering polymer foam core) or external façade materials to a high heat flux exposure over significant specimen heights from 4 to 10 m. Heat flux exposure is generated by large-scale flames from pallet stacks, wood cribs, or gas burners that are adjacent to open corners, within rooms, or near façades. During the various tests, observations are made to determine if self-sustained flame spread occurs to the top or lateral boundaries of the apparatus. Such flame spread indicates the presence of a flammability hazard for the particular type of fire scenario that is being simulated by the test method.

## SMOKE YIELD

Smoke has long been identified as the most significant hazard to people during fire.<sup>79</sup> Smoke and the toxic gases contained in it are the primary cause of fatalities in fires. Smoke can also impair visibility and prevent escape from threatened areas. The rate of production of smoke and other products of combustion is very dependent on the fire scenario (type and configuration of material burning, flaming or nonflaming combustion, level of external heat flux) as well as the scale of the fire. In addition, the ventilation air supply and stage of the fire (pre- or postflash-over) will also significantly influence the production of smoke and other species. Building codes have attempted to regulate the amount of smoke likely to be produced by various materials during a fire. Specifically, interior finishes are often required to have a smoke developed rating less than 450 when measured using the ASTM E84 tunnel test.<sup>80</sup> The smoke-developed rating is determined by comparing the light absorption curve from a test material to the light absorption results from inorganic cement board and red oak flooring, which have smoke-developed indexes of 0 and 100 respectively.

Smoke production is measured by weighing the particulates collected on a filter, by determining the optical density of

a quantity of smoke collected in a known volume, or measuring the optical density as an assumed plug flow of smoke moves through an exhaust duct. The optical density measurements in a duct flow are most convenient but also provide only an indirect measure of smoke production. Typically, the smoke produced during a test is reported as a smoke yield, which is a mass of smoke per unit mass of material burned,<sup>81</sup> with a higher smoke yield representing a greater flammability hazard for two reasons: (1) a higher yield implies that combustion products from a fire will produce more direct damage to life and property for each unit of material that burns and (2) a higher yield implies that there may be more soot in the flame to enhance radiant flame heat transfer, leading to higher heat release rates, more extensive flame spread, and higher burning rates.

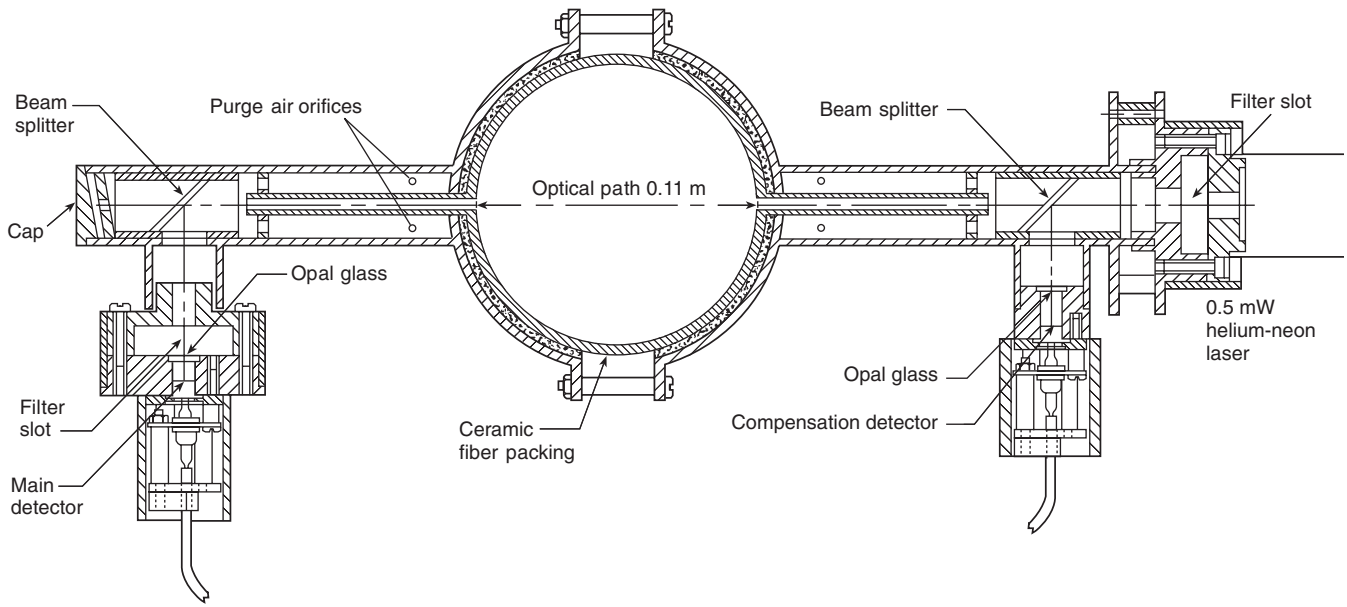
Note that every test method for flammability hazard that uses an exhaust collection hood or duct to measure heat release rate will also provide a measure of smoke generation rate using the optical density data coupled with the exhaust duct flow rate. This measurement, together with the mass loss measurement, if available, allows the smoke yield to be calculated for the evaluation of flammability hazard. Although the ASTM E84/NFPA 255 tunnel test does not measure heat release rate, this test method does provide an index representing the amount of smoke produced by the burning sample. The index is determined by using a white light source and a photocell to measure the light absorption occurring in the exhaust duct and is referenced to red oak which has a value of 100 (NFPA 255).

The cone calorimeter and fire propagation apparatus are two laboratory calorimeters that can also be used to obtain smoke obscuration data.<sup>82</sup> The attenuation of light from a He-Ne laser beam passing through the exhaust duct is measured as a function of time. An extinction coefficient is calculated from the data and used to determine a specific extinction area in the cone test methods whereas a smoke yield is calculated from a smoke generation rate in the fire propagation apparatus test methods. These equivalent quantities can be regarded as an effective material property and measure of flammability hazard. [Figure 2.3.12](#) depicts the smoke measuring portion of cone calorimeter and fire propagation apparatus.

## SMOKE YIELD TEST METHODS

### Smoke Chamber Test

The NBS smoke chamber was developed specifically to measure obscuration by smoke particulates.<sup>83</sup> The apparatus consists of a 3 ft (0.914 m) wide, 3 ft (0.914 m) high, and 2 ft (0.61 m) deep enclosure. A 3 in. × 3 in. (75 mm × 75 mm) specimen is exposed in the vertical orientation to an electric heater. Tests can be conducted with or without small pilot flames impinging at the bottom of the specimen. A white light source is located at the bottom of the enclosure, and a photomultiplier tube is mounted at the top to measure obscuration and optical density of the smoke as it accumulates inside the enclosure. This method is described in ASTM E662, *Standard Test Method for Specific Optical Density Generated by Solid Materials*.<sup>84</sup> Three tests are conducted at a heat flux of 25 kW/m<sup>2</sup> with pilot flames and without pilot flames. These conditions are referred to as



**FIGURE 2.3.12** Schematic of Laser Photometer or Smoke Measuring Portion of Cone Calorimeter (Courtesy Society of Fire Protection Engineers)

the flaming and nonflaming modes, respectively. The latter is misleading because specimens often ignite spontaneously, leading to flaming combustion without the pilot flames. The test has been subjected to criticism because the smoke generated by the specimen accumulates inside the chamber and eventually affects combustion. The test conditions, therefore, are not well controlled and partly depend on the burning behavior of the product itself.

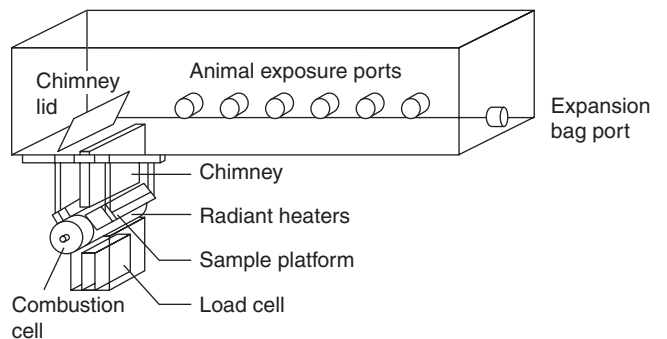
### Guide for Measurement of Fire Gases

Fires can generate not only smoke particulates but also toxic products of combustion, primarily in gaseous form. A wide range of techniques is used to measure toxic gas concentrations in fire tests, ranging from simple qualitative sorption tube methods to sophisticated spectroscopy techniques. ASTM E800, *Standard Guide for Measurement of Gases Present or Generated During Fires*,<sup>85</sup> describes the most common analytical methods and sampling considerations for many gases. Fourier transform infrared (FTIR) spectroscopy has emerged in recent years as the method of choice for real-time continuous analysis of fire gases. Animal tests have been used to determine toxic potency, but their use has become increasingly limited. One of the test procedures which minimizes the number of animal tests is described in ASTM E1678, *Standard Test Method for Measuring Smoke Toxicity for Use in Fire Hazard Analysis*<sup>86</sup> and NFPA 269, *Standard Test Method for Developing Toxic Potency Data for Use in Fire Hazard Modeling*. In this test procedure, a specimen is exposed to a radiant heat flux of 50 kW/m<sup>2</sup> and the products of combustion are collected in a 0.2 m<sup>3</sup> (7 ft<sup>3</sup>) chamber. Test duration is 30 minutes. A mathematical correction is made to the analytical measurements to account for the increase in CO production in underventilated postflashover fires. This is

important because the majority of U.S. fire deaths occur remote from the fire room, especially for fires that have proceeded past flashover. Figure 2.3.13 illustrates the smoke density test apparatus used in ASTM E1678.

### EXTINGUISHABILITY

There are very few engineering methods to determine the extinguishability of materials or material systems for use in the evaluation of flammability hazard. One method already mentioned in connection with heat release rate is the large-scale required delivered density of water (RDD) test for storage commodities (see a full description in Section 2, Chapter 7, “Theory of Fire Extinguishment”), in which a material array (typically cartons with vertical and horizontal flue spaces) burns under



**FIGURE 2.3.13** Smoke Toxicity Test Apparatus from ASTM E1678 (Source: National Institute of Standards and Technology)

an exhaust measurement hood. A fixed, known water flux is applied to the top surface of the commodity array at the time when sprinkler actuation would be expected to occur. Through multiple tests of this type, the critical water flux that will cause a permanent decay in heat release rate after the initial peak value can be determined. With regard to the flammability hazard of an isolated material surface, a laboratory measurement method to determine the critical water flux for extinguishment of horizontal (facing upward) or vertical burning material panels was described by Magee and Reitz<sup>87</sup> in the 1970s (see Section 2, Chapter 7, “Theory of Fire Extinguishment”). Obviously, the greater the water flux required for extinguishment, the greater is the flammability hazard.

## SUMMARY

By definition, any material capable of burning with a flame is considered flammable, but the flammability hazard of a material in a specific fire scenario is not easily quantified. Different aspects of flammability hazard can be defined or categorized and for each such category, a test method is available to measure the magnitude of a material characteristic that can be used to evaluate, if not quantify, flammability hazard. These different aspects of flammability include type of response to heat flux, ease of ignition, generation of heat and smoke, extent of flame spread, and ease of extinguishment. The flammability of a material is dependent on many parameters, such as its chemical composition, physical properties, geometric configuration, and combustion products. As a result, flammability is really a characterization of multiple fire hazards. There is no single measure that will adequately describe a material’s performance in a real fire scenario.

Given the large number of parameters that play a role in determining flammability hazard, it is important to use a variety of flammability test methods and models in order to have a more reliable and accurate assessment applicable to realistic fire scenarios.

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#### NFPA Codes, Standards, and Recommended Practices

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

- NFPA 253, *Standard Method of Test for Critical Radiant Flux of Floor Covering Systems Using a Radiant Heat Energy Source*  
 NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials*  
 NFPA 260, *Standard Methods of Tests and Classification System for Cigarette Ignition Resistance of Components of Upholstered Furniture*

- NFPA 261, *Standard Method of Test for Determining Resistance of Mock-Up Upholstered Furniture Material Assemblies to Ignition by Smoldering Cigarettes*  
 NFPA 262, *Standard Method of Test for Flame Travel and Smoke of Wires and Cables for Use in Air-Handling Spaces*  
 NFPA 265, *Standard Methods of Fire Tests for Evaluating Room Fire Growth Contribution of Textile Coverings on Full Height Panels and Walls*  
 NFPA 271, *Standard Method of Test for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*  
 NFPA 286, *Standard Methods of Fire Tests for Evaluating Contribution of Wall and Ceiling Interior Finish to Room Fire Growth*  
 NFPA 287, *Standard Test Methods for Measurement of Flammability of Materials in Cleanrooms Using a Fire Propagation Apparatus (FPA)*  
 NFPA 701, *Standard Methods of Fire Tests for Flame Propagation of Textiles and Films*  
 NFPA 705, *Recommended Practice for a Field Flame Test for Textiles and Films*  
 NFPA 921, *Guide for Fire and Explosion Investigations*

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