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Dedicated to Dr. John L. Bryan, for his inspiration, leadership, and support.

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CHAPTER

8

Fire Testing

Mark Campbell, Fire Forensics Research Center, Denver, CO

> "I have devised seven separate explanations, each of which would cover the facts as far as we know them. But which of these is correct can only be determined by the fresh information which we shall no doubt find waiting for us."
>
> –Sir Arthur Conan Doyle
> *The Adventure of the Copper Beeches*

KEY TERMS

autoignition temperature, *p. 355*
calorimetry, *p. 358*
fire point, *p. 358*
flash point, *p. 357*
spontaneous ignition temperature, *p. 355*

OBJECTIVES

After reading this chapter, the student should be able to:

- Recognize the value of fire testing.
- Describe the basic types of fire tests and give examples of each.
- Learn how to interpolate scaled test data to real-world scenarios.
- Appreciate the use of fire test data in the analysis and evaluation of a working hypothesis.

Fire testing is a form of physical modeling in which testing or experimentation is conducted using materials related to a case or study. Testing conducted in support of fire reconstruction can span the range from simple field tests requiring no equipment to benchtop flame tests to extensively instrumented, full-scale test burns in real buildings (as shown in Figure 8-1).

NFPA 921, 2011 ed., pt. 20.5.1, states, "Fire testing is a tool that can provide data that complements data collected at the fire scene (see *NFPA 921*, 2011 ed., pt. 4.3.3), or can be used to test hypotheses (see *NFPA 921*, 2011 ed., pt. 4.3.6). Such fire testing can range in scope from bench scale testing to full-scale re-creation of the entire event" (NFPA 2011).

Fire tests can help confirm or reject hypotheses about the fire's ignition or spread, test and validate the predictions of computational models or those of experienced investigators, or demonstrate the roles of various factors in the fire and its effects on occupants. This chapter explores, in summary form, many of the tests useful in fire investigation.

ASTM and CFR Flammability Tests

A number of test standards and methods applicable to fire investigation were listed in Table 1-3 (see Chapter 1). Several of the ASTM tests can be used to assess the ignitability of materials or the nature and speed of flame propagation, and they are discussed briefly here. However, as you will see, there are limitations to the application of results of these tests to an actual case. Many limitations are due mostly to the geometry or size of the sample.

A flame will spread much more quickly upward than it will downward or outward in the same fuel. A fire started at the top edge of a sofa back will spread much more slowly than if the same fabric is ignited at the base of the sofa. A fire ignited at the top of hanging draperies will be much more likely to cause the hooks and drapery rod to fail and collapse with the draperies, possibly resulting in dropdown ignition of materials beneath, whereas draperies ignited at the bottom are often nearly completely consumed before they cause failure of their supports.

FIGURE 8-1 Testing for fire reconstruction purposes can span the range from simple field tests requiring no equipment to extensively instrumented full-scale test burns on real buildings. *Courtesy of Michael Dalton, Knox County Sheriff's Office.*

Fire resistance properties today are sometimes built into a combination of layers of fabrics and backings that result in acceptable ignition resistance. Separating and testing the layers individually may yield very misleading results. The residual moisture in test samples also can affect their ignitability, so specimens are often conditioned for 24–48 hours under specific criteria prior to testing.

Most ASTM standard methods include an advisory comment regarding use of the method to compare materials or their performance under controlled conditions to assess the possible contributions a material *might* make under a specific set of fire conditions and not to predict what a product *will* do when exposed to different fire conditions. Some of the tests reference other entities such as the National Fire Protection Association (NFPA) and the U.S. Consumer Product Safety Commission (CPSC).

- *Flammability of Clothing Textiles (16 CFR 1610-U.S.):* This test requires that a sample of fabric 50 mm × 150 mm (2 in. × 6 in.) placed in a holder at a 45° angle and exposed to a small flame touching its surface for 1 second not ignite and spread flame up the length of the sample in less than 3.5 seconds for smooth fabrics or 4.0 seconds for napped fabrics. Test sample must be oven dried and cooled prior to the test.
- *ASTM D 1230: Standard Test Method for Flammability of Apparel Textiles (not identical with 16 CFR 1610):* CPSC requires fabrics introduced into commerce to meet requirements of *16 CFR 1610*. This test is suitable for textile fabrics as they reach the consumer or for apparel other than children's sleepwear or special protective garments. A sample of fabric 50 mm × 150 mm (2 in. × 6 in.) is held at a 45° angle in a metal holder and a controlled flame is applied to the bottom end for 1 second. The time required for the flame to proceed up the fabric a distance of 127 mm (5 in.) is recorded.
- *Flammability of Vinyl Plastic Film (16 CFR 1611-U.S.):* This test requires that vinyl plastic film (for wearing apparel) placed in a holder at a 45° angle and ignited not burn at a rate exceeding 3.0 cm (1.2 in.) per second.
- *Flammability of Carpets and Rugs: 16 CFR 1630 (Large Carpets) and 16 CFR 1631 (Small Carpets):* A specimen of carpet is placed under a steel plate with a 20.32-cm (8-in.)-diameter circular hole. A methenamine tablet is placed in the center of the hole and ignited. The duration of burning and heat release rate of the tablet duplicate those of a typical dropped match. If the specimen chars more than 3 in., in any direction, it is considered a "fail." The ambient radiant heat flux is minimal, because the sample is tested at room temperature. The ignition source is a modest 50 to 80 W flame of brief duration. Testing has shown that some carpets that pass this test will be readily ignited and spread flames if the radiant heat flux is larger as a result of a larger and more prolonged ignition source. The carpet is tested in the flat, horizontal position, so the same carpet mounted vertically *may behave very differently*.
- *ASTM D2859: Standard Test Method for Ignition Characteristics of Finished Textile Floor Covering Materials:* This method uses a steel plate 22.9 cm (9 in.) square and 0.64 cm (0.25 in.) thick with a 20.32-cm (8-in.)-diameter circular hole. A methenamine tablet is placed in the center and ignited in a draft-free enclosure. Samples are thoroughly oven-dried and cooled in a desiccator before being tested. The product fails if the charred portion reaches within 25 mm (1 in.) of the edge of the hole in the steel plate. Eight specimens are tested. The Flammable Fabrics Act (FFA) regulations require that at least seven of the eight specimens pass this test.

- *Flammability of Mattresses and Pads (16 CFR 1632-U.S.):* A minimum of nine regular tobacco cigarettes are burned at various locations on the bare mattress—quilted and smooth portions, tape edge, tufted pockets, and so forth. The char length of the mattress surface must not be more than 50 mm (2 in.) from any cigarette in any direction. The test is repeated with the cigarettes placed between two sheets covering the mattress.
- *Standard for the Flammability (Open Flame) of Mattress Sets (16 CFR 1633-U.S):* This test method is a full-scale test based on NIST research. The mattress or mattress and foundation set is exposed to a pair of T-shaped propane burners for a short time and allowed to burn freely for 30 minutes. The burners are designed to represent burning bedclothes. Measurements are taken to determine the heat release rate from the specimen and total heat energy generated from the fire. The standard establishes two test criteria, both of which the mattress set must meet to comply with the standard. (1) The peak heat release rate for the specimen must not exceed 200 kW at any time during the 30-minute test. (2) The total heat release must not exceed 15 MJ for the first 10 minutes of the test (*Federal Register* 71 (no. 50), March 15, 2006).
- *Flammability of Children's Sleepwear (16 CFR 1615 and 1616-U.S.):* Each of five 88.9 cm × 25.4 cm (35 in. × 10 in.) specimens is suspended vertically in a holder in a cabinet and exposed to a small gas flame along its bottom edge for 3 seconds. The specimens cannot have an average char length of more than 18 cm (7 in.), no single specimen can have a char length of 25.4 cm (10 in.) (full burn), and no single sample can have flaming material on the bottom of the cabinet 10 seconds after the ignition source is removed. These requirements are for finished items (as produced or after one washing and drying) and after the items have been washed and dried 50 times.
- *ASTM E1352: Standard Test Method for Cigarette Ignition Resistance of Mock-Up Upholstered Furniture Assemblies:* This test uses reduced-scale plywood mock-ups, 47 cm × 56 cm (18 in.× 22 in.), upholstered with simulations of seat, backrest, and armrests to test ignitability of furniture to dropped smoldering cigarettes. The test is used for furniture to be used in public and private occupancies such as nursing homes and hospitals. The cigarettes are positioned on each of the various surfaces and along crevices between seats, armrest, and back. The distance of char extension from each cigarette or ignition by open flame is recorded for comparison.
- *ASTM E1353: Standard Test Method for Cigarette Ignition Resistance of Components of Upholstered Furniture:* This test uses mock-ups to test individual components—cover fabrics, welt cords, interior fabrics, and filling or batting materials in the form, geometry, and combination in which they are used in real furniture. This test uses single cigarettes, but each is covered with a single layer of cotton sheeting that retains more heat and makes it a more severe test than one in open air.
- *ASTM E648: Standard Test Method for Critical Radiant Flux of Floor-Covering Systems Using a Radiant Heat Energy Source:* This test uses a horizontally mounted floor covering specimen 20 cm × 99 cm (8 in. × 39 in.) with a gas-fired radiant heater (with a gas pilot burner) mounted at a 30° angle above it that produces a radiant heat flux of 1–10 kW/m^2. The distance the flame propagates along the sample indicates the minimum radiant heat flux for ignition and propagation.

ASTM Test Methods for Other Materials

The ASTM International Committee E05 on Fire Standards identifies methods for testing other materials.

- *ASTM D1929: Standard Test Method for Determining Ignition Temperature of Plastics (ISO 871):* This test uses a cylindrical hot-air furnace to heat the test sample in a pan. A thermocouple monitors the temperature of the sample while the temperature is adjusted so that pyrolysis gases venting through the top of the chamber can be ignited by a small pilot flame held near it, which establishes the *flash ignition temperature* (FIT). The same apparatus can be used to establish the **spontaneous ignition temperature (SIT)** by eliminating the pilot flame and observing the sample visually for flaming or glowing combustion (or a rapid rise in the sample temperature). SITs for common plastics are 20°C–50°C (68°F–122°F) higher than FITs by this technique. The test requires 3 g of material for each test in the form of pellets, powder, or cut-up solids or films.

spontaneous ignition temperature (SIT) ■ See autoignition temperature.

- *ASTM E119: Standard Test Methods for Fire Tests of Building Construction and Materials:* A specimen (wall assembly, floor, door, etc.) is exposed to a standard fire exposure to evaluate the duration for which those assemblies will contain a fire or retain their integrity. A large furnace (horizontal or vertical) is used to create a standard time–temperature environment. The assembly is exposed to the prescribed conditions, and its surface temperature is measured, its structural integrity is monitored, and the time for penetration of flame through it is determined. The standard time–temperature exposure does not accurately reflect all real-world fire exposures, so the performance rating of tested building components is for comparison only.
- *ASTM E659: Standard Test Method for Autoignition Temperature of Liquid Chemicals:* A small sample (100 μL) of liquid is injected into the mouth of a glass flask heated to a predetermined temperature, and the flask is observed for the presence of a flash flame inside the flask and a sudden rise in internal temperature (as monitored by an internal thermocouple). If no ignition is observed, the temperature is increased and the test repeated until the material ignites reliably. This method establishes the *hot-flame* **autoignition temperature** (AIT) in air. Ignition delay times may also be recorded. The temperature at which small sharp rises occur in the internal temperature alone is the *cool-flame autoignition temperature.*

  The method can also be used for solid fuels that melt and vaporize or sublime completely at the test temperatures, leaving no solid residues. The test conditions are controlled by the heat transfer between the glass flask and the fuel introduced and the confined geometry of the spherical flask. In real-world ignitions, the nature of the surface and the manner of contact will determine the convective heat transfer coefficient and may modify times or temperatures. Any geometry (tube or enclosure) that keeps the fuel in contact with the hot surface is going to produce ignitions at lower temperatures than an open, flat surface, where buoyancy of the heated vapors can transport the fuel away from the heated surface.

autoignition temperature ■ The temperature at which a material will ignite in the absence of any external pilot source of heat; also referred to as the spontaneous ignition temperature.

- *ASTM D3675: Standard Test Method for Surface Flammability of Flexible Cellular Materials Using a Radiant Heat Energy Source:* This method uses a gas-fired radiant heat panel 30 cm × 46 cm (12 in. × 18 in.) in front of an inclined specimen of material 15 cm × 46 cm (6 in. × 18 in.), oriented so that ignition with a pilot flame first occurs at the upper edge of the sample and the flame front moves downward. The rate at which the flame moves downward is observed, and a flame spread index is calculated. The test is suitable for any material that may be exposed to fire. At least four specimens must be tested.
- *ASTM D3659: Standard Test Method for Flammability of Apparel Fabrics by Semi-restraint Method:* This test simulates the burning characteristics of a garment hanging vertically from the shoulders of a wearer. Test specimens are 15 cm × 38 cm (6 in. × 15 in.) (five specimens required) and are oven-dried and weighed prior to testing. The sample is hung vertically from a crossbar, and the flame of a small gas burner is positioned against the bottom edge of the fabric for 3 seconds and then removed. The weight (percentage area) destroyed by the flame and the time required are the criteria for comparison. (Cross-reference to *FF 3-71: Flammability of Children's Sleepwear, Sizes 0–6X.*)

- *ASTM E84: Standard Test Method for Surface Burning Characteristics of Building Materials:* This is the "Steiner Tunnel" test, which mounts specimens on the underside of the top of an insulated tunnel 7.6 m (25 ft) long, 30 cm (12 in.) high, and 45 cm (17.75 in.) wide. A gas burner at one end ignites the sample, and the rate of flame spread along the length of the specimen is observed and recorded. The test specimen must measure at least 51 cm × 7.32 m (20 in. × 24 ft). An optical density measurement system (light source and photocell) is mounted in the vent pipe of the apparatus. Samples of products of combustion can be taken downstream of the photometer. The upside-down configuration of this test apparatus is not often found in real-world situations except with combustible ceiling coverings.
- *ASTM E1321: Standard Test Method for Determining Material Ignition and Flame Spread Properties:* This method tests for the ignition and flame spread properties of a vertically oriented fuel surface when exposed to an external radiant heat flux. The results can be used to calculate the minimum radiant heat flux and temperature needed for ignition and flame spread. The test configuration is a large, vertically mounted specimen and a gas-fired radiant panel heater mounted at an angle to it. A gas pilot flame is used, and the rate and distance of flame spread along the length of the specimen are recorded (see Figure 8-2).
- *ASTM E800: Standard Guide for Measurement of Gases Present or Generated during Fires:* This guide describes methods for properly collecting and preserving combustion gas samples during fire tests and analytical methods for O_2, CO, CO_2, N_2, HCl, HCN, NO_x, and SO_x, using gas chromatography, infrared, or wet chemical methods. As we have seen, some fuels produce high concentrations of toxic or irritant gases under various fire conditions. Testing materials known to be present in a fatal fire may yield clues as to what role their combustion gases played in the fatality.
- *California TB 603 Standard for Mattresses, Box Springs, and Futons:* After January 1, 2005, the state of California required that bedding materials sold for residential and commercial use comply with new testing procedures. The test is designed to simulate real-world flaming ignition sources and measure the energy released from burning bedding materials. The top and side of the mattress are exposed to T-shaped gas burners for a period of time (as in Figure 8-3). Failure of the test can be either (1) a peak heat release rate of 200 kW or greater within 30 minutes after ignition or (2) a total heat release of 25 MJ or greater within 10 minutes of ignition. As of July 1, 2007, all mattresses, mattress and foundation in sets, and futons sold for residential use in the United States must pass the *16 CFR 1633* test, which is similar, except the total heat released must not exceed 15 MJ in the first 10 minutes.

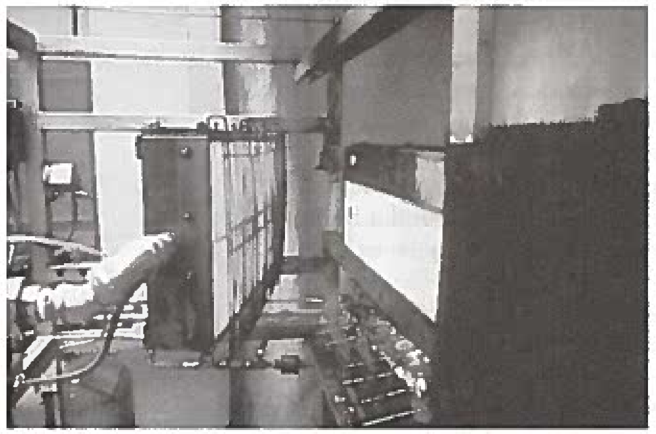

FIGURE 8-2 Surface rate of flame spread test (*ASTM E 1321*) uses a radiant heat panel at an angle to the surface being tested. *Courtesy of NIST.*

Flash and Fire Points of Liquids

Tests for flash and fire (flame) points of ignitable liquids can be as simple as placing a few drops of the fuel in a petri dish or watch glass at room temperature and waving a lighted match near the surface of the liquid. Ignition will confirm that the material is a Class I A or B flammable liquid with a flash point below room temperature (23°C [73°F]). More reliable testing requires more controlled evaporation and confinement of the vapors with a more reproducible ignition source. Flash point testing in general involves taking a quantity of liquid fuel and placing it in the cup of a water bath whose temperature is gradually increased. The cup may be open to the atmosphere or closed with a small shutter. A very small flame is introduced periodically, and the cup is observed for the presence of a brief flash of flame. The fire point of many liquids may be established by the open-cup method by increasing the temperature until a self-sustaining flame is established rather than just a flash of flame.

Closed-cup testers retain some of the vapor produced and make it easier to ignite. Closed-cup flash points are typically a few degrees lower than open-cup determinations of the same fuel.

Tests for flash and fire points of liquids include the following:

- *ASTM D56: Standard Test Method for Flash Point by Tag Closed Cup Tester:* Applicable to low-viscosity liquids with flash points below 93°C (200°F). Requires 50 mL of liquid for each test. (Sometimes abbreviated TCC.)
- *ASTM D92: Standard Test Method for Flash and Fire Points by Cleveland Open Cup Tester:* Applicable to all petroleum products with flash points above 79°C (175°F) and below 400°C (752°F) except fuel oils. Requires at least 70 mL for each test. (Sometimes abbreviated COC.)
- *ASTM D93: Standard Test Methods for Flash Point by Pensky-Martens Closed-Cup Tester:* Applicable for petroleum products with a flash point in the range of 40°C–360°C (104°F–680°F) including fuel oils, lubricating oils, suspensions, and higher-viscosity liquids. Requires at least 75 mL of fuel for each test.
- *ASTM D1310: Standard Test Method for Flash Point and Fire Point of Liquids by Tag Open-Cup Apparatus:* Applicable for liquids with flash points between −18°C and 165°C (0°F and 325°F) and fire points up to 165°C (325°F) will work at subambient temperatures. Fire point criterion: When fuel ignites and burns for at least 5 seconds. Requires 75 mL of sample for each test.
- *ASTM D3278: Standard Test Methods for Flash Point of Liquids by Small Scale Closed-Cup Apparatus:* Suitable for flash point determination of fuels with a flash point between 0°C and 110°C (32°F to 230°F) in small quantities (2 mL required for each test). Employs a microscale apparatus sold as the Setaflash Tester. Test methods similar to those for ISO 3679 and 3680 will work on subambient determinations.
- *ASTM D3828: Standard Test Methods for Flash Point by Small Scale Closed Tester:* Similar to *ASTM D3278.* Used to establish whether a product will flash at a given temperature, using 2–4 mL of sample for each test.

Owing to the multiplicity of flash point test methods, the *ASTM E502-07e1* offers a *Standard Test Method for Selection and Use of ASTM Standards for the Determination of Flash Points of Chemicals by Closed-Cup Methods* (ASTM 2007a).

FIGURE 8-3 The TB 603 test in use on a mattress. All mattresses sold in the United States for residential use after July 1, 2007, must pass the *16 CFR 1633* test, which has a total heat release limit of 15 MJ, compared with the 25 MJ limit of this test. *Courtesy of Bureau of Home Furnishings.*

flash point ■ The minimum temperature at which (under defined test conditions) the vapor being produced by a material can be ignited to produce a brief flash (not sustained) of flame.

fire point ■ The lowest temperature at which a liquid will ignite and achieve sustained burning when exposed to a test flame in accordance defined test conditions, such as, for example, *ASTM D92: Standard Test Method for Flash and Fire Points by Cleveland Open Cup Tester* (*NFPA 30*, 2012).

calorimetry ■ An analytical method used to measure the total heat of combustion of fuels.

Calorimetry

Classical bomb **calorimetry** is used to measure the total heat of combustion of fuels (as in *ASTM D4809*). The term *bomb* refers to a sealed vessel that can withstand internal pressures. The procedure involves burning a weighed specimen in a sealed container with an excess of oxygen until the specimen is completely oxidized. The heat generated by the combustion is determined by measuring the increase in temperature of the sealed vessel and using its specific heat and mass to calculate the heat released in the combustion. This test is unsuitable for fuels comprising multiple substances, as it yields the *total* heat of combustion, not the *effective* heat of combustion (which accounts for losses due to incomplete combustion).

Because almost all common fuels yield nearly the same amount of heat per mass of oxygen consumed (13 kJ/g), one could easily calculate the heat generated by measuring the amount of oxygen consumed during the combustion process. This procedure is called *oxygen consumption* (or oxygen depletion) *calorimetry*. If a specimen is burned in air and the waste products are all drawn into a system of ducts, the O_2, CO, and CO_2 concentrations can be measured. If the ventilation rate into the test chamber and through the exhaust duct is measured, the amount of oxygen consumption can be determined. Optical sensors in the ductwork can also monitor the optical density and obscuration of smoke products generated. Note that both the oxygen consumption and the heat release rate are calculated from collected data.

This approach has been refined into four general categories of size and application: cone, furniture, room, and industrial calorimeters. In the *cone calorimeter*, developed by Babrauskas at NIST and described in *ASTM E1354-11b*, a 10 cm × 10 cm (4 in. × 4 in.) specimen in a metal tray is exposed to a uniform incident radiant heat flux from a cone-shaped electric heater mounted above it (as in Figure 8-4) (ASTM 2011).

The radiant flux striking the sample can be controlled by adjusting the temperature of the heater element. A small electric arc source is introduced to ignite the plume of smoke generated by the heating and then removed. The flame and smoke vent upward through the center of the cone heater, and the gases are ducted to where the flow rate; O_2, CO, and CO_2 concentrations; and smoke obscuration are measured. The entire specimen tray is mounted on a sensitive load cell, so the mass loss is continuously measured. The analysis calculates the heat release rate (expressed per unit surface area of fuel), mass loss rate, and effective heat of combustion. Even though the samples tested are reduced scale, testing has shown that the results have a high degree of correlation with real-world fire performance (Babrauskas 1997). The system works with liquid or solid fuels (even low-melting-point thermoplastic materials) in the horizontal configuration. Wood and other rigid fuels can also be tested in the vertical configuration.

Furniture calorimeters were developed to test the heat release rate of single items of full-scale real furniture by the same method. Here, the furniture is mounted on a load cell and burned in the open, with all combustion products drawn into a vent hood. The temperature; pressure; and O_2, CO, and CO_2 concentrations are measured in the ductwork. The calculated heat release rate can then be combined with the mass loss data from the load cell to calculate the effective heat of combustion.

When multiple pieces of furniture, along with carpet, wall linings, and other fuels, are to be evaluated as a fuel package, a *room calorimeter* is used. In this case a room is built (often to a standard size of 2.4 m × 3.6 m × 2.4 m (8 ft × 12 ft × 8 ft), and the entire room becomes the "collector" for the exhaust vent. The combustion products vent through the door opening and are drawn up into the exhaust hood and measured. This arrangement allows heat release rate to be calculated constantly as fire spreads from one item to another, even culminating in near-flashover conditions.

The largest-scale devices are often called *industrial calorimeters*. These are basically a large exhaust hood with appropriate fans, ducting, and instrumentation. They are generally located in high-bay buildings. Typical measuring capacities are 12 kW (cone calorimeter), 1.5–5 MW (furniture calorimeter), 3–6 MW (room calorimeter), and 10–50 MW (industrial calorimeter). The latter would be most useful for performing fire scene reconstructions; unfortunately, most of these devices are owned by organizations (e.g., UL, ATF) that do not offer commercial testing services for fire reconstruction. Southwest Research Institute (San Antonio, Texas) has 4–10 MW calorimeters available for commercial fire reconstruction projects.

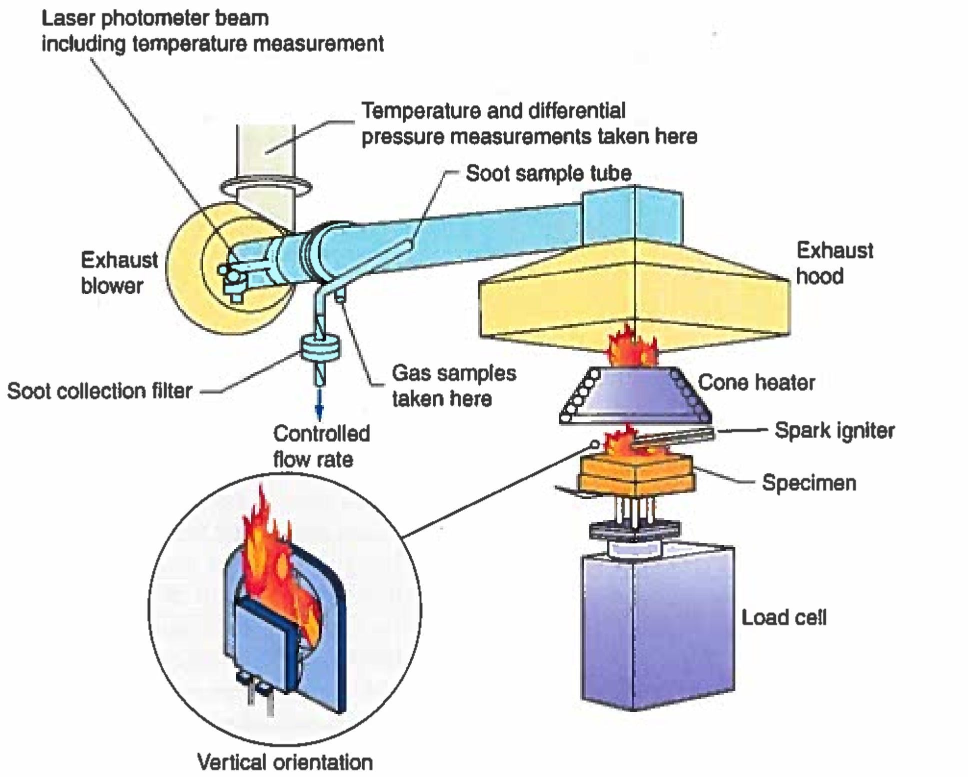

FIGURE 8-4 In the cone calorimeter, developed by Babrauskas at NIST and described in *ASTM E1354-11b*, a 10 cm × 10 cm (4 in. × 4 in.) specimen in a metal tray is exposed to a uniform incident radiant heat flux from a cone-shaped electric heater mounted above it. *Courtesy of Dr. Vytenis Babrauskas, Fire Science & Technology, Issaquah, Washington.*

Furnishings

Tests for ignitability of upholstered furniture vary widely, from cigarette ignition to small flames to larger gas-fired burners of known heat output (typically 17–40 kW). They may be applicable to standardized small-scale mock-ups of furnishings as well as to the actual items taken from the production line. Pass/fail criteria may be based on observable flame spread, penetration, percentage mass loss, peak heat release rate, quantity of smoke produced, or toxicity of fire gases.

TEST METHODS

Various test methods in use today include those described under the U.S. Code of Federal Regulations (CFR), British Standards (BS), International Organization for Standardization (ISO), ASTM, and California Bureau of Home Furnishings Technical Bulletins (TB). Krasny, Parker, and Babrauskas (2001) have assembled a comprehensive description and discussion of the current techniques, which are summarized in Table 8-1. See also *Kirk's Fire Investigation*, 7th ed., for additional information (DeHaan and Icove 2012).

TABLE 8-1 Summary of Furniture Item Flammability Tests

TEST	CIGARETTE IGNITION	FLAME IGNITION	HRR	SMOKE	TOXICITY
ISO 8191	X	X			
BS 5852	X	X			
ATSM E1352	X				
ASTM E1353	X				
NFPA 261	X				
NFPA 260	X				
California TB116, 117	X				
Upholstered Furniture Act Council	X				
BIFMA	X	X			
CFR 1632	X				
BS 6807	X	X			
Calif. TB 133		X	X	X	X
Calif. TB 129		X	X	X	X
Calif. TB 121		X		X	X
ASTM E1537		X		X	X
ASTM E1590		X		X	X
ASTM E162		X			
ASTM D3675		X			
ISO 5660			X	X	X
ASTM E1474			X	X	X
ASTM E1354			X	X	X
NFPA 264A			X	X	X
ASTM F1550M				X	
ISO TR 5924				X	
ASTM E662				X	
ASTM E906			X	X	
ISO TR 9122					X
ISO TR 6543					X
ASTM E1678					X

Source: Derived from Krasny, Parker, and Babrauskas 2001.

As with the bench-scale tests described earlier, there are limitations and cautions regarding the application of these test results to the reconstruction of real-world fires. For example, the mere passing of a particular test by a target material does not imply that it will be fire resistant or even fire safe in a real-world environment.

Other cautions to be observed include requirements for conditioning samples for 24–48 hours at a particular temperature and humidity. The investigator should be aware of the potential influence of such variables on the test result. The geometry of the test compartment is also important. The same piece of furniture may yield different heat outputs or fire patterns if tested in a corner or against a wall versus in the center of a large room that minimizes radiant feedback or ventilation effects.

The location, manner, means, and duration of ignition can play a significant role in the fire performance of furnishings. A vinyl-covered chair seat, for instance, can provide substantial resistance to small ignition sources if an ignition source is placed on the seat (PVC upholstery tends to char, intumesce, and shield the substrate). But even a small flaming source placed under the seat where the flame can contact the polyurethane padding will readily ignite the chair.

CIGARETTE IGNITION OF UPHOLSTERED FURNITURE

Cigarette ignition of upholstered furniture was a major fire cause for decades owing to the predominant use of cotton or linen upholstery fabrics over cellulosic padding of cotton, coir, kapok, or similar materials, all of which were easily ignited by a glowing cigarette.

Holleyhead (1999) published an extensive review of the literature regarding cigarette ignition of furniture. However, a great deal of misinformation once existed about the time required for such ignition to result in flaming combustion. Investigators erroneously concluded that such ignitions always required 1–2 hours, inferring that any flaming ignition in a shorter time must have been the result of deliberate ignition by open flame.

Extensive testing by the California Bureau of Home Furnishings and NIST (then NBS), first reported in the early 1980s, demonstrated that ignition time was variable. Transition to flaming combustion was reported in as little as 22 minutes from the placement of a glowing cigarette between the cushions, or between the cushions and an arm or backrest. Other tests required 1 to 3 hours, and some never transitioned to open flames and smoldered for hours before self-extinguishing. Even identically built mock-ups demonstrated a wide variety of behaviors. A statistical analysis of these results was published by Babrauskas and Krasny (1997).

Tests by the authors have demonstrated similar time and ignition results. If the fabric is torn and the cigarette drops into direct contact with cotton padding that has not been treated to be flame retardant, transition to flame has been observed in as little as 18 minutes in still air. The presence of drafts can influence the progress and increase the heat release rate of smoldering cellulosics. One informal test by DeHaan with a cigarette wrapped loosely in a cotton towel and left outside in a light, variable wind resulted in flames about 15 minutes after placement. The mechanism for transition from smoldering to flame has so far defied modeling or accurate predictions. Hand-rolled cigarettes present a lower ignition risk because they tend to self-extinguish more often than commercially made tobacco cigarettes. For references and testing of cannabis resin cigarettes on petrol-soaked clothing, see the work by Jewell, Thomas, and Dodds (2011).

According to the NFPA-sponsored website firesafecigarettes.org/, all 50 states have passed legislation mandating what is termed as "fire-safe" or self-extinguishing cigarettes. The European Union (EU) established standards for its member countries and required as of November 17, 2011, that all cigarettes sold in the EU be "reduced ignition propensity" (RIP) cigarettes. The term RIP is a more technically accurate term than "fire-safe" for these cigarettes, because it means that they have been designed to be less likely than a conventional cigarette to ignite soft furnishings such as a couch or mattress. These redesigned cigarettes will only reduce chances for cigarette ignition of upholstered materials in the future but will not prevent all ignitions. Fire-safe cigarettes typically use a banded paper with alternating high and low porosity in the bands, which causes smoldering to cease.

Latex (natural) rubber foam is also easily ignited by contact with a glowing cigarette. It should be noted that a cigarette will be consumed in a maximum of 20–25 minutes after being lit (somewhat longer if tucked between seat cushions). Ignition times longer than that result from a self-sustaining smolder in the surrounding fuel initiated by the cigarette, as confirmed by the significant quantity of white smoke that is produced for some minutes prior to flame (far more than can arise from a single cigarette).

Additional Physical Tests

SCALE MODELS

A great deal of useful information can be obtained from building scaled-down replicas of rooms or furnishings for testing, at reduced cost and complexity compared with full-scale re-creations. These models are particularly valuable for testing ignition and incipient fire hypotheses (in which the interaction of room surfaces or conditions does not play a major role).

When radiant heat or ventilation factors are involved, the test must take into account that all factors in a fire do not scale down in the same linear fashion as the room dimensions. For instance, ventilation through an opening is controlled by the area of the opening and the square root of its height. It is possible to calculate corrections for such factors, but it is not as simple as building a dollhouse, with all doors and windows in the same proportion as in full scale. Radiant heat flux falls off with the inverse square ($1/r^2$) of the separation distance, so scale-model builders must keep those relationships in mind as well.

As with all fire investigation tools available to the investigator, a *reduced-scale enclosure* (RSE) can provide a lot of information that may be very helpful and is relatively simple to build and burn. The hot smoke is dynamically a fluid, so its movement through a *full-scale enclosure* (FSE) tends to be similar to that through a RSE. In an early paper, Quintiere evaluated various scaling considerations regarding heat transfer and smoke movement (Quintiere 1989).

Current research in ventilation openings (doors) in RSEs is investigating scaling the vertical dimension but adjusting the width to maintain the entrained air mass flow rate by modifying the ventilation factor $A_0\sqrt{h_0}$, where A_o is the area of the door opening, and h_o is the height of the door opening. For example, if the scale is one-fourth (0.25), then the width of the RSE door is $\sqrt{0.25}$ (or 0.5) times the width of the FSE door. Thus, a 30-in. door opening at one-fourth (0.25) scale would be 7-1/2 in. wide, but with the adjustment of the square-root factor, the opening would be 15 in. wide. Note that only the width of the ventilation opening is adjusted (Bryner, Johnsson, and Pitts 1995).

In addition, current research appears to suggest that the furniture construction does not require precise and intricate construction. The use of standard 1/2-in. oriented-strand board (OSB) as the framework, polyurethane as the padding, and furniture upholstery as the covering appears to provide adequate fuel packages. Overall dimensions are scaled, but the thickness of the furniture is not. One style of scaled furniture cuts the center out of the OSB to form a frame from which the chairs and couches are made. They are glued or stapled to form the structure. Furniture upholstering is used to wrap the frame and glued in place. The polyurethane is covered with furniture upholstering and placed on the frame. Beds have been made of two layers of polyurethane covered with bed sheets. Simple wood structures are placed under the bed to form the bed frame. See Figure 8-5 for innovative work by Mark Campbell on scale-model demonstrations.

Current testing has shown similarities between FSE, RSE, and FDS models. Some of these similarities include calcination plots, clean-burn areas, ventilation burn patterns, flashover, backdrafts, and thermocouple data. Thermocouple plots in RSEs have shown the growth phase of the fire and the transition to flashover, turbulent mixing that occurs in the enclosure, and decay of the fire. This type of information may be used to help the investigator examine patterns, locations, and intensities.

It should be recognized that a RSE will help provide information related to fire effects but should not be used to calculate heat release rate, fire spread time, mass loss rate, gas species, or gas concentrations, as these are more difficult to scale. Heat release rate, speed of smoke movement, and time to flashover will also not be linearly correlated. This valuable information is used to help the investigator refine the working hypothesis and should never be the stand-alone research or testing.

(a)

FIGURE 8-5 (a) Quarter-scale room built by Mark Campbell and Dan Hrouda. A front view of the Reduced Scale Enclosure. The drywall front will be added and will face the door opening. Two cameras will be added: one on side A, facing the back of the room, and one on side D, facing the couch. The propane sand burner is in corner B/C. Fifteen thermocouples are located throughout the cell. *Mark Campbell, Fire Forensics Research Center, Denver, CO*

(b)

FIGURE 8-5 (b) This is a side view from side D looking toward side B just after the propane sand burner was shot off after 90 seconds. The propane sand burner is located just to the right of the couch. The heat release rate was scaled to be approximately 3 kW so it would scale to the $/^{5/2}$, as required by the scaling laws. A 100 kW fire is used in the Full Scale Enclosure. *Mark Campbell, Fire Forensics Research Center, Denver, CO*

(c)

FIGURE 8-5 (c) The fire has spread across the couch, and now the hot ceiling gases have stared to pyrolyze the chair and caused it to ignite. The thermocouples in the middle of the room help determine when the room starts the transition through flashover. *Mark Campbell, Fire Forensics Research Center, Denver, CO*

(d)

FIGURE 8-5 (d) The fire exits the Reduced Scale Enclosure, as it is now in the postflashover burning stage. The enclosure is burned for 2 minutes postflashover. The Reduced Scale Enclosure provides the investigator with another tool to help assess the various fire effects and burn patterns. *Mark Campbell, Fire Forensics Research Center, Denver, CO*

Floor or wall materials proportionally reduced in thickness may respond to thermal insult as *thermally thin* targets if they are less than a few millimeters thick and may respond differently than thicker sections of the same material. Special materials may be selected for models of walls and ceiling so their thermal behavior will duplicate, in scale, that of gypsum or plaster walls.

FLUID TANKS

A great deal of the information used to create and test the models of smoke and hot gas movement discussed in previous chapters was developed in *fluid tanks* with no fire or smoke at all. Because the buoyancy of the hot gases relative to normal room air drives the movement of smoke in a building, the same process can be simulated by using two liquids of different densities (such as fresh- and saltwater). If one fluid is dyed, its movement and mixing can easily be observed and recorded. See Figure 8-6 for innovative work on fluid tank model demonstrations.

Often, a scale (one-eighth to one-fourth) model of the room(s) is built of clear Plexiglas and immersed and inverted in a large tank of the lighter (less dense) liquid. The heavier liquid is then introduced into the model in a manner to simulate the generation of gases from a fire in the room. Scaling factors are important, and the relative densities and viscosities of the liquids have to be calibrated to simulate the mixing of gases in a buoyant flow, but the technique can provide answers to some investigative problems and confirm or reject computational models and hypotheses (Fleischmann, Pagni, and Williamson 1994).

FIELD TESTS

Identification of the first fuel ignited is critical to the reconstruction process. If the first fuel is more easily susceptible to open-flame ignition than to glowing- or hot-surface ignition (for example, such fuels as natural gas, gasoline vapors, or polyethylene plastic), the fire scene search can focus on the appropriate type of potential ignition sources. Cellulosic fuels or other natural materials such as wool are much more easily ignited by hot-surface sources like discarded cigarettes or glowing electrical connections. Most such materials can be reliably identified by visual inspection, but information as to their behavior when ignited is much more within the realm of expertise of the fire investigator.

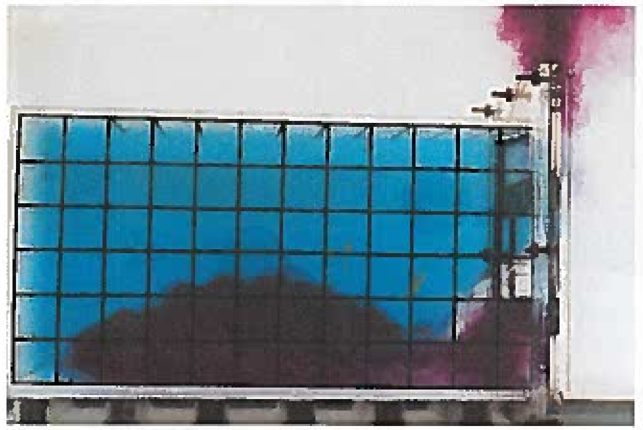
(a)

FIGURE 8-6 (a) Side view of quarter-scale fluid tank demonstrating cool denser fluid (representing cool air) entering the chamber through the lower half of the door opening after the door (extreme right) is opened. The buoyant fluid (blue) is venting from the top of the opening. These tests were conducted to evaluate flows and mixing in possible backdraft events in compartment fires. *Courtesy of Dr. Charles Fleischmann, University of Canterbury, Christchurch, New Zealand.*


(b)

FIGURE 8-6 (b) Quarter view of half-scale fire test chamber. An underventilated burner in the closed chamber has produced a hot, fuel-rich, buoyant smoke layer. When the door (on the right) is opened, the buoyant smoke escapes, and cool fresh air flows in the bottom of the opening to mix with the hot smoke. When ignited by a pilot flame at the far end, the flame progresses quickly along the premixed interface as a backdraft event. This behavior was predicted by the fluid tank tests shown in (a). *Courtesy of Dr. Charles Fleischmann, University of Canterbury, Christchurch, New Zealand.*

A simple *flame* or *ignition susceptibility test* using a match or lighter applied to one corner while the small test sample is held vertically in still air will reveal how readily it will ignite and whether it will support flaming combustion when the ignition source is removed, as described in *NFPA 705* (NFPA 2009). However, *NFPA 701* (NFPA 2010) is now considered the preferred practice.

Under the test conditions, cellulosic materials support a yellow flame with a gray smoke. When the flame is blown out, these materials tend to support glowing combustion. The ash left behind is gray to black in color and powdery or crumbly in texture. There is no droplet of hard-melted residue. Thermoplastic synthetic materials melt as they burn, so melted, burning droplets result. They also tend to shrink and shrivel as they melt and often burn with a blue-based flame, with smoke ranging from negligible to white (polyethylene) to heavy and inky black (polystyrene). These materials do not support smoldering combustion.

Thermosetting resins are usually more difficult to ignite than other fuels. They tend to smolder when flame is removed, produce an aggressive smoke, and leave a hard, semiporous residue. Elastomers (rubbers) can be either natural (latex) or synthetic and can behave like either. Some will burn very readily; others, like silicone rubber, burn much more reluctantly. Silicone rubber leaves a brilliant white, powdery ash, whereas other elastomers leave a hard, dark porous mass. Samples of any unknown material suspected of being the first fuel ignited should be collected for laboratory analysis if there is doubt concerning their contribution to the ignition or growth of the fire.

Caution should be exercised in both conducting and interpreting such informal ignition tests. The *NFPA 705* test has been criticized as being subjective and variable owing to the procedures and personnel involved. There is also a risk of injury to personnel and a reported cause of serious accidental fires. A strong suggestion is to use *NFPA 701: Methods of Fire Tests for Flame Propagation of Textiles and Films* when conducting flame or ignition susceptibility tests (as in Figure 8-7) (NFPA 2010).

NFPA 701 is basically a flammability test that applies to typical straight-hanging fabrics such as curtains, draperies, and window treatments. The test determines a fabric's rate of flammability subjected to certain ignition sources. In *NFPA 701* tests, the material is hung vertically and subjected to flame for a prescribed time period, is observed to see whether it self-extinguishes, is measured for char length, and is observed to see whether it does not continue to burn after reaching the floor of the test chamber.

NFPA 701 Test Method No. 1 applies to single-layer fabrics and to multilayer curtain and drapery assemblies. Vinyl-coated fabric blackout linings are tested according to *NFPA 701* Test Method No. 2. *NFPA 701* cautions that materials applied to surfaces of buildings or interior finishes should be tested in accordance with *NFPA 255: Standard Method of Test of Surface Burning Characteristics of Building Materials,* or *NFPA 265: Standard Methods of Fire Tests for Evaluating Room Fire Growth Contribution of Textile Coverings on Full Height Panels and Walls.*

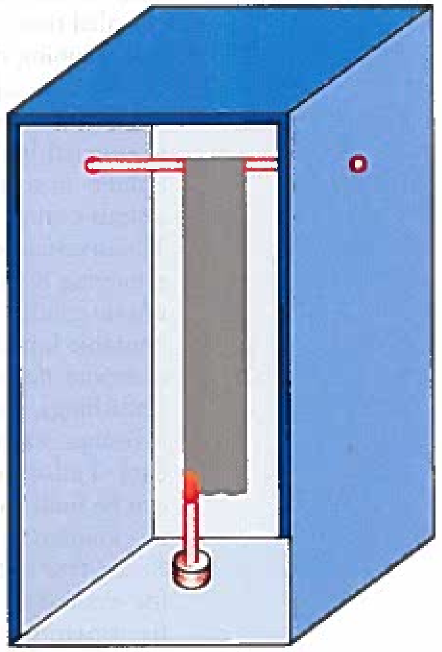

FIGURE 8-7 The *NFPA 701* test is used for small-scale testing of the flammability of fabrics. The *NFPA 701* apparatus uses a free-hanging vertical strip [150 mm × 400 mm/(6 in. × 16 in.)] of the fabric to be tested in an enclosed test chamber. The flame from a laboratory burner is applied at the bottom of the strip for 45 seconds and then removed. The flame spread behavior of the fabric is observed, and after extinguishment, the residue is weighed.

The presence of fire retardants may significantly affect ignition and flame spread. Materials like carpet are much more easily ignited from a corner or edge than if the same ignition source is applied to the center of the specimen. Ignition and flame spread are enhanced by vertical sample orientation and may be retarded by draft or moisture in the sample, so the results should be noted but not taken as proof of identity or of actual fire behavior (NFPA 2009).

FULL-SCALE FIRE TESTS

Considerable knowledge has been gathered from fire tests conducted in real buildings slated for demolition. It is rare that the dimensions, ventilation, and construction materials of a test building will match those conditions of a specific fire that is being studied, but a great deal of reliable knowledge about fire behavior has been gleaned from these tests. Aside from physical suitability, there are often issues of fire exposure to surrounding properties, environmental concerns, logistics of access, and limitation of fire protection services. If such buildings are used, provisions should be made for multiple video camera viewports and the inclusion of thermocouple arrays and radiometers, as described next.

DeHaan found a house nearly identical to one in which six fire fatalities occurred. The test house had been scheduled for demolition. It was repaired and refurnished to duplicate the initial fire scene. Thermocouples, gas analyzers, and video cameras were used to document fire tests with accelerated and nonaccelerated ignitions. The test data revealed that a nonaccelerated fire could have been responsible for the structural damage and trapping the victims very quickly on the upper floor (DeHaan 1992).

Because of a number of training-fire deaths in the United States, fire departments have been considerably more reluctant to expose their personnel to the risks of large fires in original buildings. The majority of fire personnel recognize the value of training firefighters in such structures and plan live training burns in accordance with the safety provisions outlined in *NFPA 1403: Standard on Live Fire Training Evolutions* (NFPA 2012). The investigator should be aware that those provisions include covering floor openings, removing features such as glass windows and doors as well as debris contributing to an unsafe condition, identifying and evaluating all exits, and using only limited fuel loads (no ignitable liquids or gases). The resulting fire behavior and, most important, fire patterns therefore do not generally conform to those features of fires in buildings with normal furnishings, doors, glass windows, and intact ceilings and roofs. It is suggested that fire investigators not attempt to use such firefighting exercises to gather behavior/pattern data. Full-scale rooms that duplicate particular conditions and control other variables can be built for fire tests.

Guidance for room fire experiments is given in *ASTME 603: Standard Guide for Room Fire Experiments* (ASTM 2007b). This guide addresses assembling tests to be used for evaluating the fire response of materials, assemblies, or room contents in specific fire situations that cannot be evaluated in small-scale tests. This guide can assist those planning full-scale compartment-fire experiments and points out issues that should be resolved before testing commences. For example, *ASTM E603* suggests that a typical compartment size should be 2.4 m × 3.7 m (8 ft × 12 ft), with allowances for a 2.4-m (8-ft) high ceiling. The standard-size doorway (0.80 m ×2.0 m high) should be located in one wall, and the top of the doorway should be at least 0.4 m (16 in.) down from the ceiling to partially contain smoke and hot gases. The guide also recommends instrumentation having provisions for measuring the optical density of smoke, temperatures, and heat fluxes in the compartment. The documentation and controls necessary are also described.

CASE EXAMPLE 1

Cubicle Construction

Effective room mock-up cubicles can be assembled at low cost for full-scale tests. Based on a design by Mark Wallace, these are basically four 2.43 m × 2.43 m (8 ft × 8 ft) wood-framed panels (typically wood studs on 61-cm (24-in.) centers with gypsum wallboard, with a similar panel resting on top to form a ceiling (see Figure 8-8). A larger unit can easily be constructed, and designs provide for a knockdown wall that can easily be removed after the test to facilitate documentation.

Doors and windows can be cut as needed. A header must be left above each door 25–45 cm (10–18 in. deep). Cubicles are easily erected on four wood pallets covered with 13-mm (0.5-in.) sheet plywood or on (2 in. × 4 in. or 4 in. × 4 in.) joists. Since these are intended for short-duration (<30 min) tests, lack of insulation will not usually affect the results of interior fires. Electrical outlets can easily be added.

Viewports are easily added by cutting holes approximately 25 cm × 30 cm (10 in. × 12 in.) in size in one or more walls near floor level. An unframed piece of ordinary window glass is then glued to the *interior* surface of the wall using silicone sealant (and allowed to harden for 24 hours before the fire). The absence of a frame means that the entire sheet of glass is exposed to the same heat flux and will not develop the same stresses that cause failure before flashover. Experience reveals that such windows will usually last until flashover. Heat-resistant glass such as that used in fireplace screens or oven doors can ensure integrity postflashover if that is desired.

A *thermocouple* is a sensor for measuring temperature and consists of two different metal alloys joined together (twisted or welded) at one end. When that junction is exposed to heat, it generates a small voltage somewhat proportional to the temperature. The most common is Type K (Chromel/Alumel) and must be properly connected to extension cables with respect to their polarity to function correctly. Its most useful temperature measurement range is −200°C to 1250°C (−328°F to 2282°F). For a good source of commercial documentation and materials, consult the Omega Engineering Corporation website (www.omega.com/).

Thermocouples can easily be added through small holes drilled through the gypsum where desired. A minimum of three thermocouples on one wall is suggested: one near the ceiling, one midlevel, and one approximately

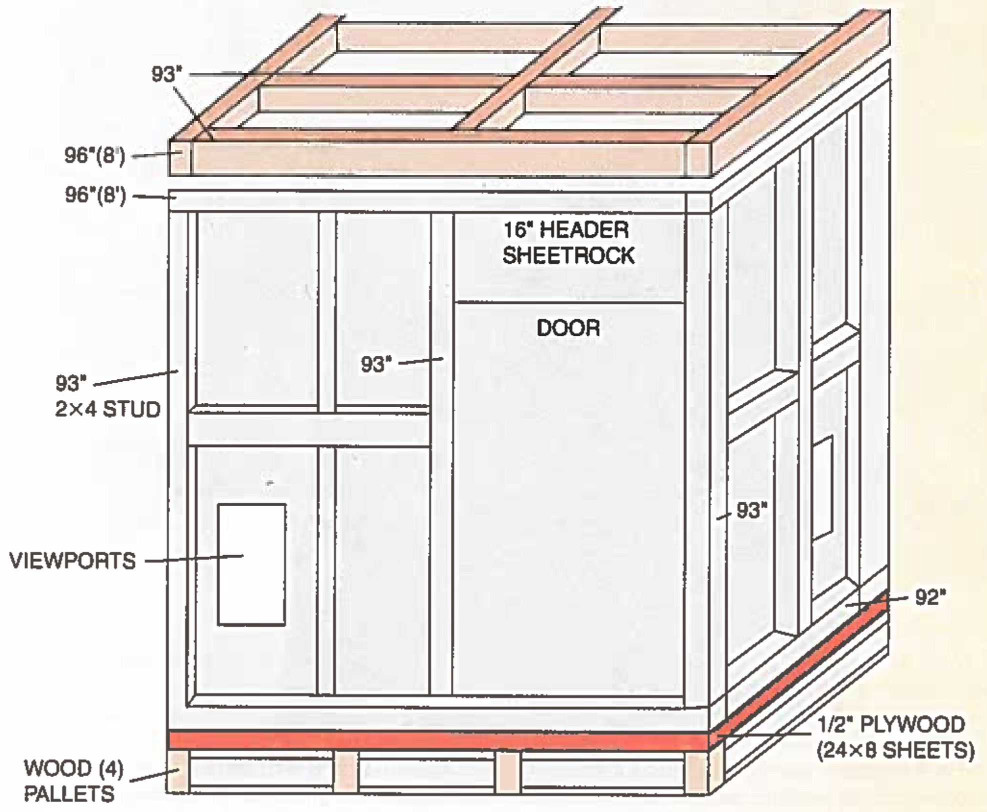

FIGURE 8-8 Effective room mock-up cubicles can be assembled at a low cost for full-scale tests. *Courtesy of J. D. DeHaan.*

15 cm (6 in.) above the floor at a point well away from the door or other vents. A second set can be installed on the opposite side of the room, or additional thermocouples can be placed inside the door header (to record flameover) or above target fuel packages. They can be shielded with a small-diameter metal, ceramic, or glass tube leaving only the tip exposed. The smallest-diameter thermocouples that are practicable should be used, since larger wire gauges lead to systematic depression in the measured temperatures. A wire size of 24 AWG is often suitable. Larger AWG numbers indicate a smaller wire diameter; however, thinner thermocouple wires can be more difficult to work with and more prone to breakage under field fire testing conditions. Data are best captured on a digital data logger such as Picolog, although they can also be captured on a video camera monitoring digital outputs of several individual meters at once for later manual transcription.

Such cubicles allow creation of environments that closely simulate real rooms (additional 1 m × 2.5 m [4 ft × 8 ft] segments can be added for larger rooms) while keeping safety risks to a minimum and reducing hazards for personnel (e.g., toxic material, asbestos exposure, or structural collapse). See Figure 8-9 for an example of a postflashover effect created in such a test cubicle. One entry wall can be framed separately so it can be easily opened and laid flat on the ground after the fire for ease of examination and photography. Video recordings should be made of all tests using multiple cameras and synchronized time clocks wherever possible. A visual and audio cue should accompany ignition so that it marks $t = 0$ on all recordings simultaneously. The small size (2.5 m × 2.5 m [8 ft × 8 ft]) will produce flashover in less time (approximately 30 percent less) than a typical 3 m × 4 m (10 ft × 13 ft) room given the same fuel load.

Scientifically valid small-scale tests can be conducted to test flame spread ignitability without special equipment as long as possible roles of the test variables are taken into account. For instance, carpet or furniture can be tested in the open with the realization that it may burn very differently if tested in a compartment because of the radiant heat reflected back from walls and ceiling and changes to ventilation conditions.

FIGURE 8-9 Results of postflashover fire in a furnished 2.4 m × 2.4 m (8 ft × 8 ft) office cubicle. Note extensive destruction of synthetic carpet and combustion of drywall paper on right. Glass viewport in right-rear corner failed prior to flashover. Note clean-burn ventilation pattern extending up the rear wall, and extensive damage to carpet beneath the opening. There was only carpet and pad in the right-rear corner. *Courtesy of J. D. DeHaan. Tests courtesy of California Association of Criminalists and Huntington Beach Fire Department.*

Carpets need to be secured to the floor in the same manner as in the actual structure. Synthetic carpets shrink and curl as they burn. If the edges lift, the combustion of the carpet can be significantly enhanced and distort the heat release rate and fire patterns. Carpets must be backed with the same pad as during the fire being duplicated, since interaction between the pad and the carpet can cause self-sustaining combustion although neither material may sustain flame spread when exposed separately.

The ignition source used should duplicate the one known to be involved, or various kinds should be tested. For instance, polypropylene carpet will resist ignition by a single dropped match at room temperature, as it will pass the required methenamine tablet test; however, the carpet will self-sustain combustion if exposed to a slightly larger ignition source such as a burning crumpled sheet of newspaper or any additional external heat flux. Once ignited, such carpet will sustain combustion at rates up to approximately 0.5–1 m^2/hr (5–11 ft^2/hr) with small flames about 5–7 cm (2–3 in.) tall.

If a fire test is conducted in a compartment, care must be taken that the major fuel packages are located in the same position in each test (or in the same position as in the scene being replicated). Packages in corners will burn differently than packages against the wall or in the middle of the room. A large fire located away from an open door will burn differently than the same fire set near the door (Figure 8-10). Changes in the compartment vent opening size and location will alter air flow during testing and will influence the resulting fire patterns. Ventilation-effect fire patterns are to be expected if the fire test is allowed to proceed to postflashover (ventilation-limited) burning.

(a)

FIGURE 8-10 (a) Interior of 2.4 m × 2.4 m (8 ft × 8 ft) cubicle after a 20-minute fire. Bed on right was ignited by open flame to clothing on top and required nearly 16 minutes to be completely involved. The room went to flashover less than 1 minute later, igniting carpet and chair in left-rear corner (with pig haunch and legs). Note the extensive combustion of the corner of the bed nearest the door (ventilation effect). Glass viewport in rear corner failed prior to flashover. *Courtesy of J. D. DeHaan.*

(b)

FIGURE 8-10 (b) View from doorway of same compartment after removal of bed, chair, and remaining carpet from left side of compartment. Note exposed areas of carpet and 13-mm (0.5-in.) plywood floor consumed in less than 4 minutes of postflashover fire and top-down burning of 5 cm × 10-cm (2 in. × 4 in.) wood floor joists. No accelerants were used. *Courtesy of J. D. DeHaan. Tests courtesy of the Iowa Chapter of the IAAI.*

CASE EXAMPLE 2 Iowa Cubicle Tests

Examples of the valuable data obtained from cubicle tests include tests conducted September 25, 2002, in Waterloo, Iowa. In these tests, the Iowa Chapter of the International Association of Arson Investigators (IAAI) and the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) built two cubicles of nearly identical fuel loads.

Each cubicle contained a synthetic upholstered chair, a wood dresser, curtains, a kitchen chair, and synthetic carpet with polyurethane padding. The first cubicle was ignited by an open flame to the skirting of one chair. This fire required 10.5 minutes to grow to flashover. The second cubicle was ignited with gasoline across the middle of the floor, with flashover occurring in approximately 70 seconds. Both cubicles experienced the same maximum temperatures and same damage to the carpet and wood floor despite the difference in time to reach flashover. The tests served as a good example of physical reconstruction and data gathering.

Figures 8-11 through 8-21 detail the Iowa cubicle tests.

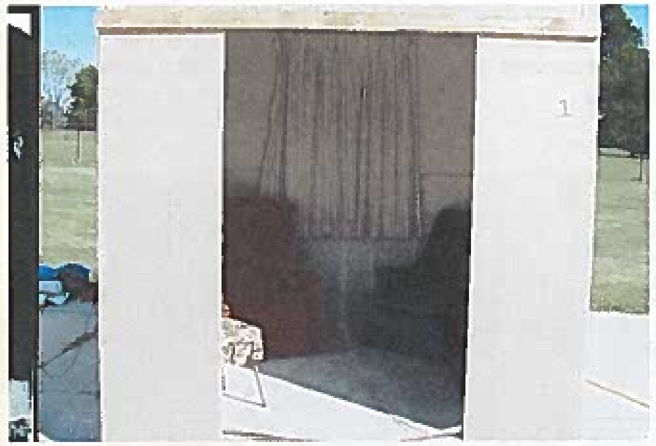

FIGURE 8-11 Prefire view of the furnished 2.4 m × 2.4 m (8 ft × 8 ft) cubicle with drywall walls and ceilings. The fire was ignited on the skirt of the chair on the left. *Photo courtesy of Special Agent Mike Marquardt, CFI, ATF, Grand Rapids, MI. Test courtesy of the Iowa Chapter of the IAAI.*

FIGURE 8-12 Postfire view after 13 minutes, which was postflashover for 5 minutes. *Photo courtesy of Special Agent Mike Marquardt, CFI, ATF, Grand Rapids, MI. Test courtesy of the Iowa Chapter of the IAAI.*

FIGURE 8-13 Pattern on floor showing intense charring of plywood and irregular destruction of carpet and pad, which is most extensive at the door. *Photo courtesy of Special Agent Mike Marquardt, CFI, ATF, Grand Rapids, MI. Test courtesy of the Iowa Chapter of the IAAI.*

FIGURE 8-14 Same cubicle with furniture replaced in its prefire positions. Note the floor-to-ceiling combustion direction patterns on the second chair and dresser. *Photo courtesy of Special Agent Mike Marquardt, CFI, ATF, Grand Rapids, MI. Test courtesy of the Iowa Chapter of the IAAI.*

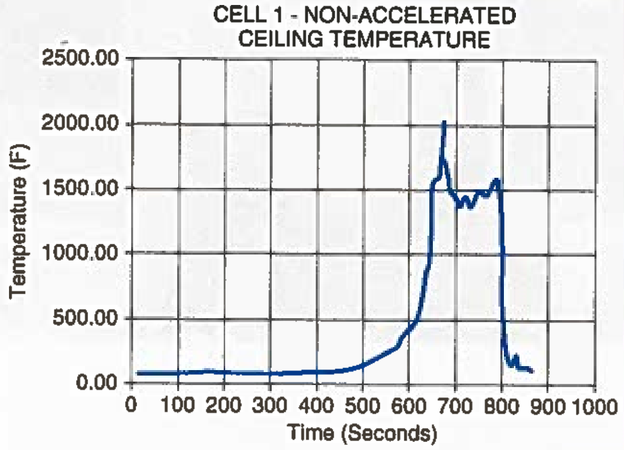

FIGURE 8-15 Temperature plot for the thermocouple tree in the center of the compartment at 0.3-m (1-ft) intervals. Note postflashover temperatures of approximately 816°C (1500°F). *Photo courtesy of Special Agent Mike Marquardt, CFI, ATF, Grand Rapids, MI. Test courtesy of the Iowa Chapter of the IAAI. Data courtesy of David Sheppard, Fire Protection Engineer, ATF Research Laboratory, Ammendale, MD.*

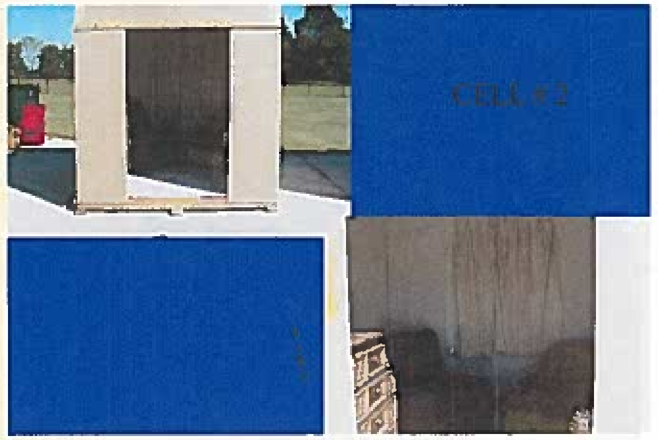

FIGURE 8-16 Prefire views of cubicle furnished in the same fashion as previously. The thermocouple tree is in the center of the cubicle. *Photo courtesy of Special Agent Mike Marquardt, CFI, ATF, Grand Rapids, MI. Test courtesy of the Iowa Chapter of the IAAI.*

FIGURE 8-17 Accelerated cubicle fire approaches flashover temperature at 60 seconds. *Photo courtesy of Special Agent Mike Marquardt, CFI, ATF, Grand Rapids, MI. Test courtesy of the Iowa Chapter of the IAAI.*

FIGURE 8-18 Postfire view after 4 minutes of gasoline-accelerated fire. The ceiling and front drywall collapsed from firefighting action. Note protected areas on walls behind both large chairs. *Photo courtesy of Special Agent Mike Marquardt, CFI, ATF, Grand Rapids, MI. Test courtesy of the Iowa Chapter of the IAAI.*

FIGURE 8-19 Floor patterns indistinguishable from that of nonaccelerated fire. Note destruction of carpet and padding and charring of floor in areas toward door, where no accelerant was poured. *Photo courtesy of Special Agent Mike Marquardt, CFI, ATF, Grand Rapids, MI. Test courtesy of the Iowa Chapter of the IAAI.*

FIGURE 8-20 Reconstruction of furniture placement. Note fire patterns on chairs outward from the rear center of the floor, where the accelerant was poured. *Photo courtesy of Special Agent Mike Marquardt, CFI, ATF, Grand Rapids, MI. Test courtesy of the Iowa Chapter of the IAAI.*

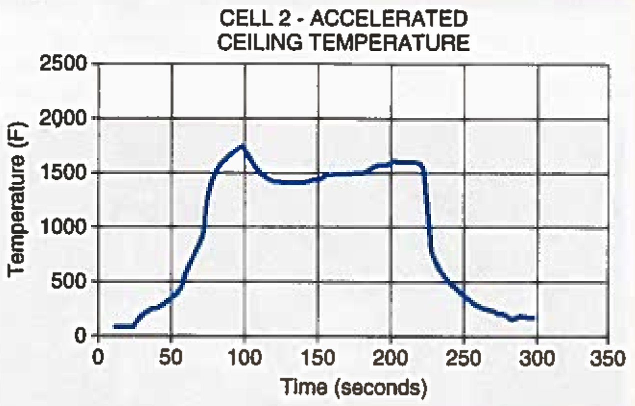

FIGURE 8-21 Temperature plot for thermocouple tree. Note ultrafast fire growth to flashover at 70–90 seconds. Postflashover period was approximately 130 seconds. *Photo courtesy of Special Agent Mike Marquardt, CFI, ATF, Grand Rapids, MI. Test courtesy of the Iowa Chapter of the IAAI. Data courtesy of David Sheppard, Fire Protection Engineer, ATF Fire Research Laboratory, Ammendale, MD.*

CASE EXAMPLE 3 Large-Scale Tests

The most sophisticated (and most expensive) form of full-scale testing is the re-creation of an entire compartment in a laboratory with calorimetry, radiometry, continuous gas sampling, and video monitoring. An excellent example of this type of large-scale fire study was the re-creation of the entire seating bay of the Stardust Disco, conducted at the Fire Research Station, Garston, UK (FRS 1982).

The single-component or furniture mock-up tests described previously are useful for gauging ignitability and fuel properties, but only a full-scale reconstruction (such as the Stardust test) can reveal the complex interactions between the growing fire and the various fuels that, in that case, resulted in the rapid growth to flashover of a small initial fire.

There are very few facilities in the world that can provide the resources necessary. NIST, Factory Mutual Engineering, Underwriters Laboratories, California Bureau of Home Furnishings (Department of Consumer Affairs), Aberdeen Proving Grounds, Building Research Establishment (Garston, UK), and Southwest Research Institute all have large burn laboratory and testing facilities. These facilities have provided invaluable testing for many fire investigators over the years, often at no cost to public agencies.

The ATF Fire Research Laboratory (FRL), Ammendale, Maryland, is a scientific fire research laboratory dedicated to supporting many research needs of the fire investigation community. It also houses ATF's National Forensic Laboratory. The FRL was designed by a team of fire scientists, engineers, and fire investigation specialists from NIST, Factory Mutual Engineering, Underwriters Laboratories, Hughes Associates, and the University of Maryland.

An example of a large-scale test, simplified for the purposes of a single demonstration, is shown in Figures 8-22 through 8-25, corresponding to 3, 8, 11, and 14 minutes after initiation of a room fire, respectively. The BRE Fire Research Station staff assembled a 2.5 m × 3.75 m × 2.4 m (8.2 ft × 12.4 ft × 8 ft) re-creation of a living room (lounge) under the 9 m × 9 m (30 ft × 30 ft) calorimeter in the Large Burn Hall at the FRS.

FIGURE 8-22 Full-scale living room fire test at 3 minutes after ignition, with only wastebasket and newspapers alight (incipient fire stage). *Courtesy of J. D. DeHaan. Test courtesy of FRS, Building Research Establishment, Garston, UK.*

FIGURE 8-23 Full-scale living room fire test at 8 minutes after ignition. Draperies have burned almost completely; dropdown has ignited chair and table in far-left corner (growth phase). *Courtesy of J. D. DeHaan. Test courtesy of FRS, Building Research Establishment, Garston, UK.*

FIGURE 8-24 Full-scale living room fire test at 11 minutes after ignition. Fire is postflashover, with maximum heat release rate of 5.2 MW observed at 10.7 minutes. Carpet is fully involved. *Courtesy of J. D. DeHaan. Test courtesy of FRS, Building Research Establishment, Garston, UK.*

FIGURE 8-25 Full-scale living room fire test at 14 minutes after ignition. Wood cabinet at left is alight. Filled with the remaining draperies, it will sustain a large fire that grows to 2 MW, then decays. Sofa and chairs are almost completely consumed (decay phase). *Courtesy of J. D. DeHaan. Test courtesy of FRS, Building Research Establishment, Garston, U.K.*

The structure was wood frame with ceramic fire insulation board liner (to permit reuse of the basic structure). The interior was lined with gypsum plasterboard, and the floor was covered with vinyl-backed carpet tiles (over a layer of sand to protect the concrete floor of the burn hall). There was a shallow 25-cm (10-in.) header across one side, which was otherwise left entirely open to simulate a "patio room" enclosure. This very large opening would provide enough air to ensure that the fire would not be ventilation limited even if it went to flashover. From the relationship for maximum mass flow of air through an opening of area A_o and height H_o,

$$\dot{m}_{\text{air}} = 0.5A_0\sqrt{H_o} = (0.5)(8.06)(1.46) = 5.88\,\text{kg/s}, \tag{8.1}$$

and since 1 kg of air will support 3 MJ of heat release,

$$\dot{Q}_{\text{max}} = (3000\,\text{kJ/kg}^3)(\dot{m}) = 17{,}640\,\text{kW}. \tag{8.2}$$

The ventilation limit for this room would be of the order of 15–17 MW. This calculation assumes 100 percent efficiency. At 50 percent, $\dot{Q}_{\text{max}}$ would be 8825 kW (8.8 MW).

The furnishings included non-flame-retardant draperies (no window); wood tables, chairs, and cabinets; a polyvinyl chloride beanbag chair; miscellaneous newspapers and books; and a three-seat sofa of recent production. This sofa was made using flame-retardant fabrics that delayed the growth of the fire substantially.

Three Chromel/Alumel thermocouples were placed in the room to monitor gas temperatures at ceiling and breathing level. Data from those thermocouples were logged every second during the test. The fire gases were collected in the calorimeter hood above (not visible in Figure 8-23).

Heat release rate and CO, CO_2, and O_2 gas concentrations were monitored continuously in the calorimeter. Continuous video recordings were made and still photos were taken by observers at 30-second to 1-minute intervals.

The newspapers in the wastebasket at the far end of the sofa (near the beanbag chair) were ignited by open flame. The heat release rate of this test is shown in Figure 8-26, and the temperatures are shown in Figure 8-27. They can be compared with the development stages of the fire shown in Figures 8-22–8-25.

This fire test was allowed to continue to burn for 25 minutes, and the remaining flames were then extinguished by water spray. Owing to the sustained postflashover burning in the room, there were no reliable indicators of duration or direction of propagation remaining on visual inspection. The absence of such indicators in postflashover rooms is one of the basic problems for fire investigators in their fire reconstruction analysis for such extended fires.

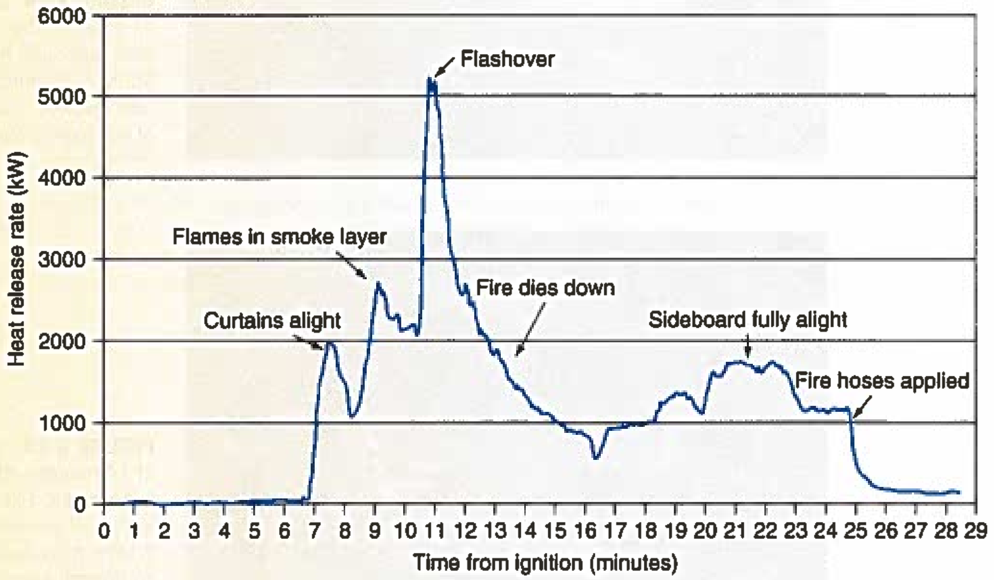

FIGURE 8-26 Plot of heat release rate versus time derived from data recorded in full-scale fire test. *Data courtesy of FRS, Building Research Establishment, Garston, UK.*

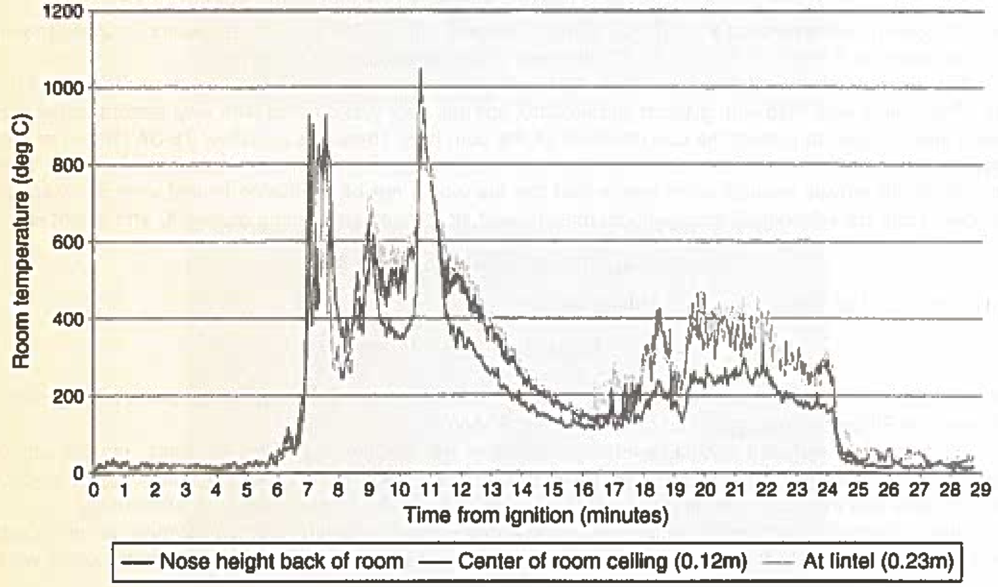

FIGURE 8-27 Plot of recorded temperatures versus time derived from data recorded in full-scale room fire test. *Data courtesy of FRS, Building Research Establishment, Garston, UK.*

This demonstration of fire development showed that when a single major fuel package such as a living room sofa is flame retardant, the growth to flashover can be delayed considerably (a 1990-vintage sofa would have promoted flashover in a similar room in less than 3 minutes if ignited by open flame in a similar fashion). Data from such tests can be used to confirm the accuracy of time and condition predictions of models, corroborate witness statements, demonstrate what stage of a fire might have incapacitated or killed a victim trapped in it, or demonstrate the role furnishings or fire protection systems may have in preventing future fires.

A series of full-scale fire tests were carried out under the auspices of the U.S. Fire Administration, National Institute of Justice (NIJ), National Association of Fire Investigators (NAFI), and Eastern Kentucky University by Ron Hopkins, Patrick Kennedy, and their co-investigators. The most recent series concerned the survivability of fire patterns in postflashover tests (Hopkins, Gorbett, and Kennedy 2009). Some of their results are shown in Figure 8-28.

These full-scale test burns provided a considerable amount of data concerning fire pattern development and evolution during fire growth and spread. The test burns demonstrated that fire pattern predictability is discernible during pre– and post–full room involvement fires and patterns can persist through brief postflashover fire exposure. The full-scale tests demonstrated that the fire patterns described in current literature are correct and when used properly can assist in the determination of the origin of a fire. Researchers found that if properly conducted, postfire testing utilizing full-scale burns and computer fire modeling may assist in the understanding of fire pattern development and fire growth.

Tests on postflashover fires include those by Carman (2008, 2010), who reported the results of tests at a 2005 fire training conference on fire dynamics led by ATF. The seminar included tests using two identical one-room cells with standard-size doorways, each burned for 7 minutes. Hours later, 53 fire investigator–students, who had not observed the fires, were asked to briefly examine the cells and identify the quadrant of each cell where they thought the fires had originated. The results showed that only 5.7 percent of the students correctly identified the quadrant of origin in each cell. Those who identified an incorrect origin typically reported they were misled during their analyses by extensive postflashover-generated burn patterns.

The authors note that these examinations of the scenes were only cursory inspections during which the investigators were unable to use accepted techniques, which would have included char depth measurements, burn pattern analysis, vector analysis, fire modeling, and laboratory examinations.

FIGURE 8-28 Room fire tests conducted at Eastern Kentucky University revealed that postflashover burning of short duration (2–4 min) does not obliterate V patterns and other useful fire patterns. (a) Fire pattern on wall near origin in postflashover bedroom test shows V pattern extending out from origin. Fire started on bed, flashover occurred at 790 seconds, and extinguishment at 1005 seconds. Postflashover fire duration: 215 seconds (3.6 min). *Courtesy of Ron Hopkins, TRACE Fire Protection and Safety, Richmond, KY.*

(b)

FIGURE 8-28 (b) Fire pattern on wall near origin in postflashover living room test shows V pattern extending out from origin, and effect of major thermal plume from sofa. Fire started on sofa, flashover occurred at 640 seconds, and extinguishment at 836 seconds. Postflashover fire duration: 196 seconds (3.2 min). *Courtesy of Ron Hopkins, TRACE Fire Protection and Safety, Richmond, KY.*

CASE EXAMPLE 4 Investigation of a Multiple-Fatality Dormitory Fire

At approximately 4:30 a.m. on January 19, 2000, a fire occurred on the third floor of the north wing of Boland Hall, a dormitory on the South Orange, New Jersey, campus of Seton Hall University. The fire resulted in the deaths of three students and injury to more than 50 other individuals. The fire origin was determined to have been on a sofa along the west wall of the third-floor common area student lounge, and the fire cause was classified as incendiary.

BUILDING DESCRIPTION

Boland Hall is a freshman dormitory located in the northwest corner of the Seton Hall University grounds. This facility comprises two sections: South Boland, a five-story building constructed in the 1950s; and North Boland, a six-story building constructed in the 1960s. The two building sections are of similar construction and are connected with a corridor at each floor level. The building construction is Type II (noncombustible) with concrete floor slabs and masonry walls (NFPA 2008). The building had a fire alarm system with manual pull stations and smoke detectors. It also had a wet standpipe system but was not equipped with automatic sprinkler protection when this incident occurred. Figures 8-29 and 8-30 show the general layout of this building.

The North Boland building floor plan is a T-shape with a long corridor oriented east–west (north corridor) that is intersected at its midpoint by a shorter corridor (center corridor) that connects to South Boland. The north corridor is approximately 81 m (266 ft) long and varies in width between 2.13 m (7 ft) and 1.52 m (5 ft). The center corridor is 1.52 m (5 ft) wide and measures 14.45 m (47 ft 5 in.) from its intersection with the north corridor to the connection with South Boland. The ceiling height in the corridors is approximately 2.41 m (7 ft 11 in.) measured slab to slab, and 2.24 m (7 ft 4 in.) floor to suspended ceiling. There are three stairways for this building accessible by the north corridor. One is located at each end of north corridor, and one is at the midpoint adjacent to the intersection with the center corridor. There are 40 dormitory rooms, accommodating approximately 84 residents on the third floor of North Boland. The fire occurred in the third-floor lounge area of North Boland. This lounge area is adjacent to the T-intersection of the north and center corridors and is open to the corridors, as shown in Figures 8-30 and 8-31. The east side of the lounge area serves as the elevator lobby for this section of the building. The lounge measures 18.13 m (26 ft 8 in.) by 7.11 m (23 ft 4 in.) with the same ceiling height as the corridors. Two smoke detectors were located on the ceiling of the lounge. One was located near the center of the lounge area, and the other was adjacent to the elevator lobby area.

FIGURE 8-29 Aerial view of Boland Hall, from Haynes and Morris 2007. *Reproduced Courtesy of Interscience Communications, Ltd.*

The lounge area contained three sofas that were located against the south wall, the west wall, and adjacent to the north corridor. These sofas were crate-style furniture pieces with heavy wood frame construction and fabric-covered polyurethane foam cushions. A wood-framed bulletin board was mounted on the west wall over one of the sofas. The dimensions of the bulletin board were approximately 2.44 m (8 ft) wide by 1.22 m (4 ft) high. The bulletin board material was a medium-density fiberboard covered with decorative paper.

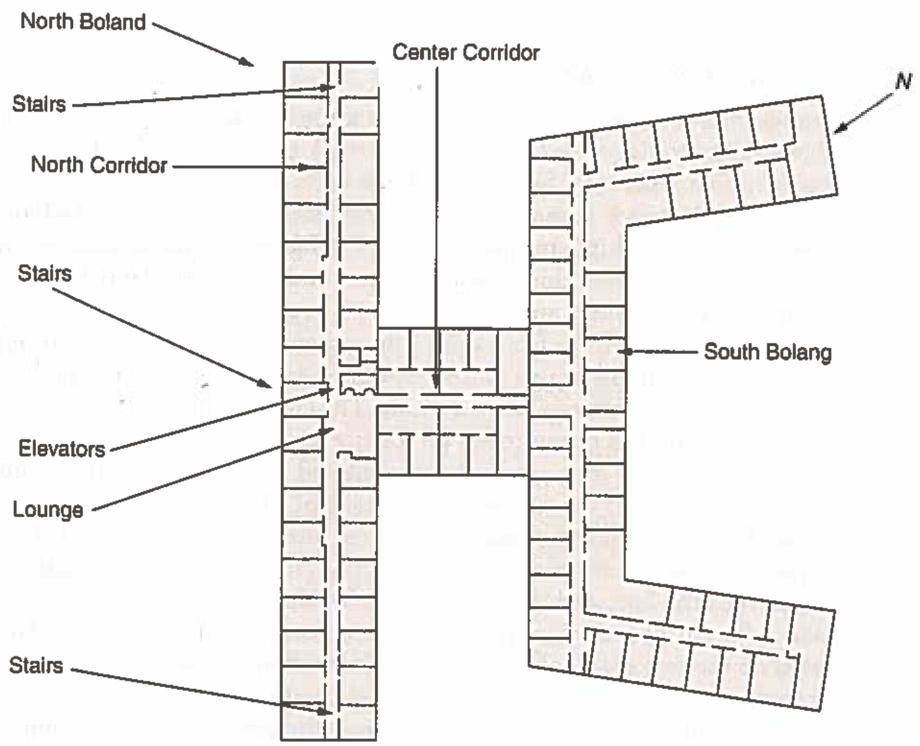

FIGURE 8-30 Diagram of third floor of Boland Hall, from Haynes and Morris 2007. *Reproduced courtesy of Interscience Communications, Ltd.*

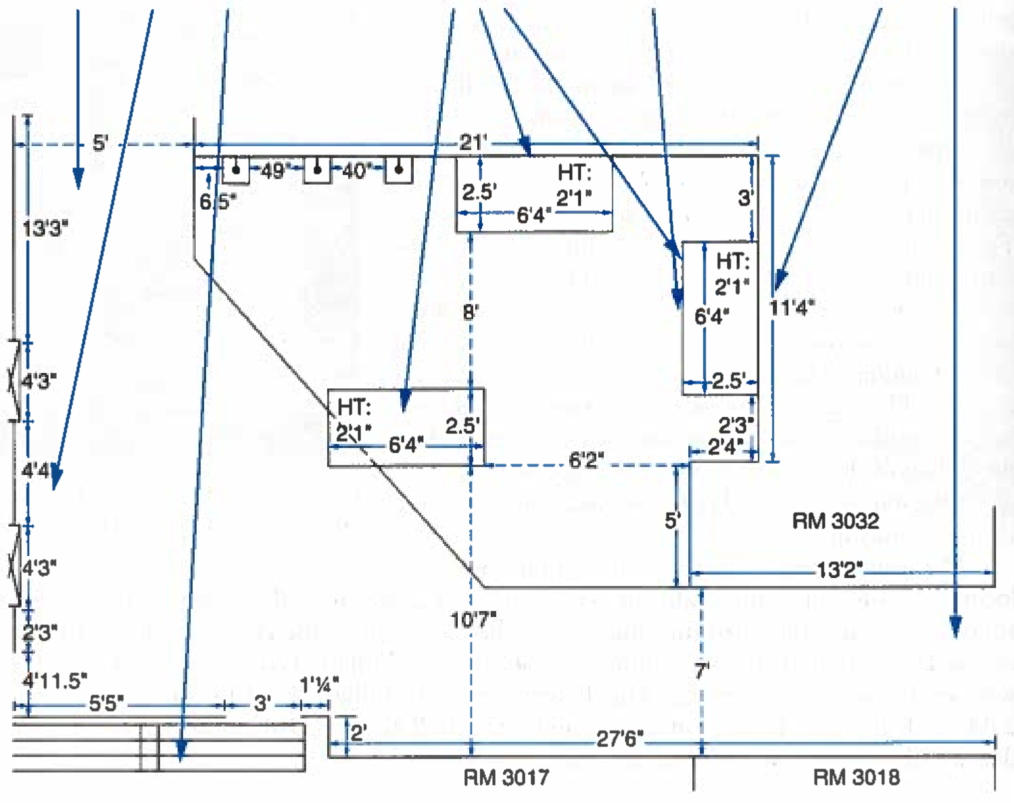

FIGURE 8-31 Diagram of third-floor lounge of North Boland Hall, from Haynes and Morris 2007. *Reproduced courtesy of Interscience Communications, Ltd.*

FIRE DEPARTMENT RESPONSE

The South Orange Fire Department received notification of the fire at approximately 4:32 a.m. and immediately dispatched an engine and truck company. Each of these pieces of apparatus was staffed with four firefighters. Both units arrived on scene at approximately 4:37 a.m., and the truck company officer established incident command and reported a working fire with multiple trapped victims. Firefighters reported that on arrival they observed smoke coming from third-floor windows and several students hanging out of windows calling for help (Frucci and Irwin 2001, 5).

The truck company set up on the front side of the structure and initiated rescue efforts using the aerial ladder. Firefighters also placed extension ladders against the building to third-floor windows to assist with rescue operations. The engine company was positioned behind the aerial apparatus and began to set up for fire suppression operations.

The truck company officer and one firefighter entered the structure with a high-rise hose pack and were directed to the fire area by a resident of the building. On reaching the third-floor landing of the north center stairs these firefighters could see fire in the lounge area through a glass panel in the stairway door. They connected the hose line to the stand pipe, charged the line, and then entered the lounge area from the stairway. The lounge area and adjacent corridors were charged with heat and thick smoke. The fire was concentrated on the two sofas located against the south and west walls of the lounge area. These firefighters stated that when they entered the lounge area, neither sofa had flames extending to ceiling height and that the fire was extinguished within one minute of their opening the hose line nozzle (Frucci and Irwin 2001, 5). After this initial fire attack was complete, the truck company officer returned to the first floor, and the firefighter remained in the third-floor lounge cooling the area with the water spray. The fire was marked under control by 4:44 a.m., but fire department search and rescue operations continued for some time owing to the heavy smoke conditions and the number of occupants remaining in many areas of the building (Sullivan 2000, 1).

Emergency medical services personnel set up on-scene triage, treatment, and patient transfer areas. These personnel provided emergency care and transportation for approximately 55 civilian casualties and four firefighters. Many of these victims sustained smoke inhalation and thermal burn injuries; at least five suffered serious and permanent injury. Three student residents died during this fire; all were from third-floor dormitory rooms. Two of the victims were found in the third-floor lounge area, and one was found in his dormitory room located at the west end of the main corridor (Frucci and Irwin 2001, 6).

SCENE PROCESSING

Examination and Excavation This fire was investigated by the Essex County Prosecutor's Arson Task Force, with assistance from the South Orange Police Department, and ATF. The first investigator on location received a briefing about the incident from fire department command and then began processing the scene. Initial steps in the scene processing included a walk-around of the building perimeter and a walk-through of the fire-affected building sections. During these preliminary scene examination steps, the investigator made observations and notes regarding fire progression indicators, fire suppression and rescue operations, and fire victim locations.

Investigators continued processing by photographing and sketching the fire area to document the scene. The bodies of the three fire victims were removed from the scene and transported to the medical examiner's office for autopsy. A canine and handler team conducted an examination of the scene for ignitable liquids recorded no alerts. Electrical wiring and fixtures in the fire area were examined and eliminated as potential causes of the fire. No evidence of extension cords or electrical appliances was found during a thorough search and excavation of the lounge area. No ashtrays, lighter, or other evidence of cigarette smoking was found in the lounge area.

The excavation of the fire scene continued with examination and removal of the debris down to the floor of the lounge. The entire lounge area and the remains of the three sofas were carefully excavated and examined. On completion of the scene processing, investigators concluded that the origin of the fire was on the sofa located against the west wall of the third-floor lounge, as shown in Figure 8-32 (Frucci and Irwin 2001, 9–14).

Witness Information Shortly after the fire scene excavation and examination were completed, investigators began interviewing residents of Boland Hall. More than 200 witness interviews were conducted, and 130 formal statements were taken. Witnesses were able to provide descriptions of the lounge before the fire. A few witnesses provided descriptions of the early fire development. Others described conditions in the lounge area just minutes before the fire was discovered. Several witnesses described an incident that occurred earlier in the morning before the fire. A student pulled paper from the bulletin board over the sofa against the west wall of the lounge. This paper was draped across this sofa, covering most of its seating area.

ENGINEERING AND SCIENTIFIC SUPPORT

The original request for engineering support and assistance was received from scene investigators within days of the fire's occurrence. The initial response to this request by an ATF fire protection engineer (FPE) was to provide some general heat release data and flame height calculations for common upholstered furniture items. A basic methodology

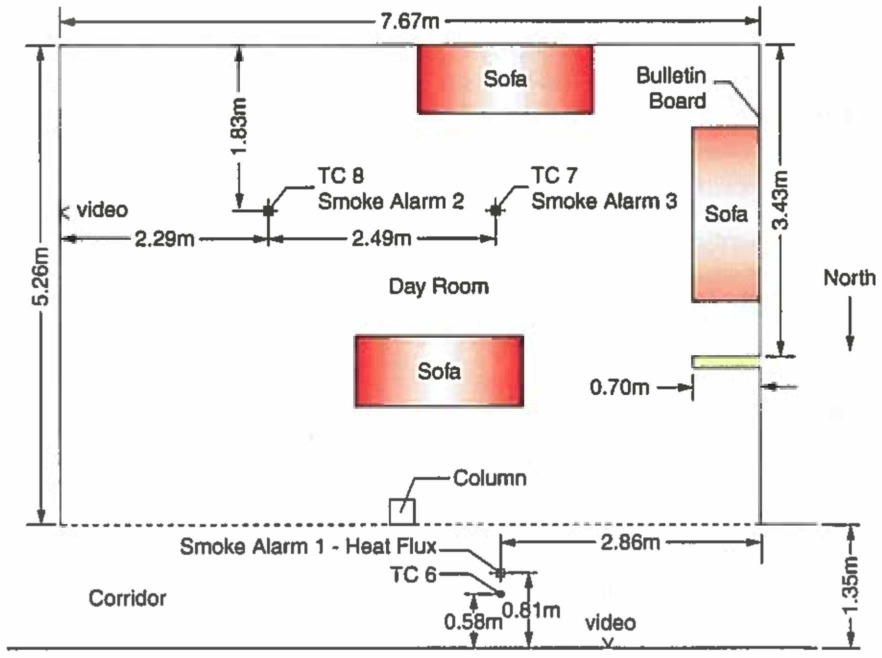

FIGURE 8-32 Diagram of day room showing sofa arrangement and instrumentation locations, from Haynes and Morris 2007. *Reproduced courtesy of Interscience Communications, Ltd.*

for incorporating this information into a simple timeline to describe possible fire development scenarios was also provided.

At the time of this investigation ATF and the NIST Building and Fire Research Laboratory, Fire Research Division, had in place a Memorandum of Understanding (MOU) and Reimbursable Agreement, which allowed the agencies to combine resources, share technical expertise, instrumentation, and facilities when conducting experiments and tests in fire research and measurement in support of arson investigation.

NIST and ATF fire protection engineers met with ATF investigators and members of the Essex County, New Jersey, Prosecutor's Office Arson Task Force on May 11, 2000. At the conclusion of this meeting a site visit of Boland Hall was conducted to collect information required for experimental set up and analysis. Data collected during this site visit included basic floor plans, sketches, limited photographs of fire-damaged areas, and measurements of significant building elements on the third floor. Samples of sofa cushions and ceiling tiles were provided for small-scale experiments and cone calorimeter testing to be conducted by NIST.

In May 2000 an ATF Special Agent assigned to the Charleston, South Carolina, ATF office notified an ATF FPE that a number of dormitory buildings were available to ATF and NIST for fire research and training. The buildings were slated for demolition as part of the Myrtle Beach Air Force Base Redevelopment Plan. In August 2000 ATF and NIST engineers visited the Myrtle Beach Air Force Base site to determine if these buildings were suitable for use to conduct fire experiments to support this investigation and various ATF and NIST fire research projects. The dormitory buildings were in reasonable condition and offered a wide range of fire experiment opportunities. The cooperation of the Myrtle Beach Fire Department and the Myrtle Beach Air Force Base Redevelopment Authority made these structures a viable location for conducting the necessary fire experiments to support this investigation.

SMALL-SCALE EXPERIMENTS

Cone calorimeter testing of the sofa cushion and ceiling tile materials was conducted by NIST in June 2000. The initial purpose of this testing was to provide material data for a planned computer modeling designed to support the large-scale dormitory experiments.

A series of small-scale ignition experiments on sofa cushion materials and decorative craft paper were conducted by NIST in August 2000 and January 2001. These experiments were designed to characterize the ignition propensity of these materials when subjected to open flame and smoldering cigarette ignition sources. The results of these small-scale ignition experiments are reported in final format in an NIST Letter Report of Test dated January 23, 2002 (Madrzykowski 2002).

LARGE-SCALE EXPERIMENTS

On September 20, 2000, NIST and ATF conducted a series of full-scale experiments in support of both this investigation and a U.S. Fire Administration (USFA)–funded research project. This joint project was part of a USFA initiative to improve fire safety in college housing. The objective of the study was to compare the levels of hazard created by room fires in a dormitory building with and without automatic fire sprinklers in the room of fire origin. Three fire experiments were conducted: (1) sprinklered, (2) unsprinklered with limited ventilation, and (3) unsprinklered with increased ventilation, all initiated in a day room area open to the corridor of the dormitory. The experiments were conducted on the first floor of a three-story building formerly used as a military dormitory. The building construction consisted of poured concrete floor and ceiling deck with concrete block walls. The vertical distance between the floor and the concrete ceiling was 2.60 m (8 ft 6 in.). No floor covering was installed. A drop ceiling, composed of fire-resistant aspen wood fiber tiles, was installed in the day room and corridor areas. Each ceiling tile was approximately 0.61 m (2 ft) by 1.22 m (4 ft) and 25 mm (1 in.) thick.

In the first of these experiments fire suppression began automatically with the activation of a sprinkler system installed for these experiments. This system consisted of four standard response sprinklers, with activation temperatures of 74°C (165°F) located under the drop ceiling of the day room. This sprinkler system was part of the NIST research project to examine the fire development, the spread of hot gases down the corridors, and the effectiveness of an automatic sprinkler system in suppressing the fire. In tests 2 and 3, manual fire suppression by Myrtle Beach Fire Department personnel was initiated approximately 15 minutes after ignition.

Each experiment utilized three sofas. Each of the sofas used for the site of ignition were similar in construction. Each was manufactured with an exposed wood frame and fabric-covered polyurethane foam. The ends of the sofa were composed of solid wood measuring 0.76 m (30 in.) wide, 0.58 m (23 in.) high, and 44 mm (1.75 in.) thick. The ends of the sofa were attached together with front and back solid wood supports. Each sofa had three back cushions and three seat cushions. The polyurethane was covered with a thin layer of polyester batting, which was covered with a textile material. The back cushions were approximately 0.61 m (24 in.) wide, 0.38 m (15 in.) high, and 0.18 m (7 in.) thick. The seat cushions were approximately 0.61 m (24 in.) wide, 0.53 m (21 in.) deep, and 0.20 m (8 in.) thick.

In experiment 1, the ignition sofa was similar in construction to the sofas used in experiments 2 and 3; however, two different types of upholstered sofas were used as "target" fuels in experiment 1. The target sofas were built with a wood frame and had seat cushions filled with polyurethane foam and back cushions filled with polyester batting. In experiments 2 and 3, all three sofas were similar.

The sofa used for the ignition site was located on the west wall of the day room, 0.91 m (3 ft) from the south wall. The second sofa was located on the south wall, 1.83 m (6 ft) from the west wall. The front face of the third sofa was located 3.2 m (10 ft 6 in.) north of the south wall, and the west side of the sofa was positioned 2.6 m (8 ft 6 in.) from the west wall, as shown in Figure 4.

A bulletin board was located above the sofa on the west wall. The dimensions of the bulletin board were 2.44 m (8 ft) wide by 1.22 m (4 ft) high. The bulletin board material was a medium-density fiberboard. It was 12 mm (0.5 in.) thick and was attached directly to the wall. The bulletin board material was framed with wood molding approximately 63.5 mm (2.5 in.) wide by 12 mm (0.5 in.) thick. Two sheets of craft paper were partially pulled down from the bulletin board and draped across the sofa. Each piece of paper was approximately 2.33 m (7 ft 7.75 in.) wide by 0.91 m (3 ft) high. In test 1 the paper was attached directly to the gypsum board wall; no bulletin board was in place.

Temperatures were measured with 0.51-mm (0.02-in.) nominal diameter bare-bead Type K thermocouples. Ten arrays of thermocouples were installed over the length of the corridor, and two thermocouple arrays were installed in the day room area. Each thermocouple array had a thermocouple located 25 mm (1 in.), 0.305 m (1 ft), 0.610 m (2 ft), 0.910 m (3 ft), 1.22 m (4 ft), 1.52 m (5 ft), and 1.83 m (6 ft) below the ceiling.

Thermocouple arrays in the corridor were located along the centerline of the corridor. The arrays were spaced on 7.62- m (25- ft) intervals, with the exception of the arrays near the east and west ends of the corridor.

Three pairs of Gardon-type heat flux gauges were installed near thermocouple arrays 4, 5, and 6. The heat flux gauges that were positioned closest to the day room, adjacent to thermocouple array 6, had a design heat flux level of 227 kW/m^2 [20 $Btu/(ft^2 \cdot s)$]. The next pair of heat flux gauges positioned to the west, adjacent to thermocouple array 5, had a design heat flux level of 114 kW/m^2 [10 $Btu/(ft^2 \cdot s)$]. The last pair of heat flux gauges, installed adjacent to thermocouple array 4, had a design heat flux level of 57 kW/m^2 ([5 $Btu/(ft^2 \cdot s)$]. Each pair of gauges consisted of one gauge facing the ceiling and the other gauge facing the day room. The height of the gauges facing the ceiling was approximately 0.91 m (3 ft) above the corridor floor or 1.17 m (3 ft 10 in.) below the suspended ceiling. The height of the gauges positioned horizontally toward the fire was approximately 0.86 m (2 ft 10 in.) above the corridor floor or 1.22 m (4 ft) below the suspended ceiling.

Commercially available ionization smoke alarms were used. The alarms were mounted under the suspended ceiling in the day room and along the corridor. Each alarm was separately connected to the data acquisition system. The voltage change, as measured across the battery terminals at its alarm point, served as the data marker for the alarm time. New smoke alarms were used for each experiment.

Each experiment was documented using thermally protected video cameras. Two video cameras captured an east to west and a north to south view of the day room. Both cameras were installed close to the floor. A third camera was installed on the floor in the vent at the west end of the corridor looking east.

The Essex County, Prosecutor's Office Arson Task Force supplied the ignition sofa in experiment 1 and all three sofas used in each of the other experiments (2 and 3). The ceiling tile material used in these experiments was similar to that identified in Boland Hall. The building geometry and furniture arrangement for these experiments was established based on the furniture arrangement and building geometry of the third-floor student lounge area of Boland Hall. The location of the smoke alarms in the day room and corridors was selected based on the smoke detector arrangement in Boland Hall. The duration of experiments 2 and 3 (ignition to manual fire suppression) was established based on the timeline of events of the fire at Boland Hall. In experiments 2 and 3, an ATF FPE ignited the bulletin board paper with a single paper match at approximately the same location along the front edge of the sofa center seat cushion. This ignition scenario was chosen for consistency between experiments and to aid in testing the hypothesis of the original fire scene investigators as to the initiation of the fire at Boland Hall.

These experiments were documented in the draft report Day Room/Corridor Fire Experiments: Draft Report of Test with cover letter dated March 12, 2001, and in NISTIR 7120, Impact of Sprinklers on Fire Hazard in Dormitories: Day Room Fire Experiments, published in June 2004 (Madrzykowski, Stoup, and Walton 2004). These reports provide detailed descriptions of the experimental configuration, furnishings, instrumentation, and experimental procedure. They also provide the results, including experiment timelines, smoke alarm activation times, temperature data, and heat flux data.

ANALYSIS

The series of small-scale ignition experiments on the sofa cushion materials and decorative craft paper conducted by NIST were designed to characterize the ignition propensity of these materials when subjected to open flame and smoldering cigarette ignition sources. The results of these ignition experiments showed that the smoldering cigarette did not cause ignition of the craft paper alone, the sofa cushion foam alone, or the craft paper on the sofa cushion sample. These experiments did show that the open flame of a single burning match was sufficient to cause ignition of each initial fuel type considered—the craft paper, the sofa cushion foam, and the sofa cushion assembly. The qualitative results from these experiments indicated that a burning match was more likely to ignite the given samples than a smoldering cigarette.

Two full-scale fire experiments were conducted at the Myrtle Beach Air Force Base, both were unsprinklered and were initiated in a day room area open to the corridor of a dormitory. These experiments were set up to have a building geometry and fuel configuration similar to that of the third-floor student lounge area of Boland Hall and are referred in the NIST report as Experiment 2 and Experiment 3. Both experiments were initiated by ignition of the bulletin board paper with a single paper match at approximately the same location along the front edge of the sofa center seat cushion.

In Experiment 2 the fire grew rapidly from ignition of the bulletin board paper and quickly spread to the entire seat and back cushions of the ignition sofa. The fire grew to sufficient intensity to cause ignition of the sofa positioned along the south wall of the day room and began to cause thermal damage to the sofa adjacent to the corridor, positioned as shown in Figure 8-32. The peak temperatures near the ceiling ranged from 780°C (1436°F) at thermocouple array 7, to 120°C (248°F), at thermocouple array 1 near the east end of the corridor. The maximum temperature at the west end of the corridor was 170°C (338°F). Analysis of the temperature and heat flux data for this experiment showed that the fire grew for approximately 7 minutes and then began to decrease in intensity. The temperatures throughout the structure peaked at approximately 400 seconds (6.7 minutes) and then steadily declined. These temperature profiles along with the video record indicated that the fire became ventilation limited and as a result decreased in intensity until extinguished by the Myrtle Beach Fire Department. The postfire analysis of the day room area also supported this observation—specifically, the damage to the sofas, ceiling, and walls, and the amount of combustible material that remained of all three sofas.

This ventilation-limit cause for the decreasing fire was considered during the setup for Experiment 3, and changes were made in the ventilation openings. In Experiment 3, five sleeping room doors were left open on the east end of the corridor. Each of these sleeping rooms had windows that opened to the outside. This change resulted in increased temperatures relative to Experiment 2. The peak temperatures near the ceiling ranged from 900°C (1652°F) at thermocouple array 7 to 240°C (464°F) at thermocouple array 1 near the east end of the corridor. The maximum temperature at the west end of the corridor was 230°C (446°F).

In Experiment 3 the fire grew rapidly from ignition of the bulletin board paper and quickly spread to the entire ignition sofa seat and back cushions, similar to Experiment 2. The fire continued to grow in intensity until it became fully developed and involved all three sofas and caused damage to the suspended ceiling. The ceiling tiles began to burn, and the ceiling suspension grid failed in areas, dropping ceiling tiles to the floor.

The fire was suppressed by Myrtle Beach Fire Department after approximately 15 minutes. When the fire suppression crew entered the corridor and day room area, the smoke level was close to the floor, and visibility was limited. The main body of fire was quickly extinguished with minimal water application from a single hand line. There were small spot fires at several locations in the day room and corridor, some of which were attributed to burning ceiling tiles. This account of the fire and the suppression sequence was similar to the accounts of the firefighters who made the initial attack on the fire in Boland Hall.

The postfire analysis of the day room area showed that the fire consumed most of the sofa cushions. The fallen and fire-damaged ceiling tiles could also be seen as debris piled on the floor. Comparison of the postfire photographs of the sofas and corridor after Experiment 3 with the fire scene photographs of the sofas and corridor of Boland Hall showed striking similarity.

CONCLUSION

The small-scale ignition experiments on the sofa cushion materials and decorative craft paper conducted by NIST showed that the smoldering cigarette did not cause ignition of the craft paper alone, the sofa cushion foam alone, or the craft paper on the sofa cushion sample. These results supported the hypothesis of the scene investigators that the fire on the sofa was not likely to have been ignited by a carelessly discarded cigarette. An open flame, however, could have constituted a competent ignition source for any of these first fuels.

The large-scale fire experiments conducted at the Myrtle Beach Air Force Base both had similar early fire development. This fire growth was similar to that described in witness accounts of residents in Boland Hall during the early stages of that fire. The fire in Experiment 2 became ventilation limited before suppression.

The growth and development of the fire in Experiment 3 was consistent with that of the fire in Boland Hall during both the early stage and the later stage right up to suppression. The accounts of the firefighters and the postfire analysis of the damage in both the Boland Hall fire and Experiment 3 supported this comparison. These similarities between the fire in the third-floor student lounge of Boland Hall and the large-scale fire experiments conducted at Myrtle Beach Air Force Base supported the hypothesis and the ultimate conclusions of the scene investigators about the origin and cause for this fire.

Following the ATF and NIST testing, investigators concluded that the fire had been intentionally set through the introduction of an open flame to construction paper from a bulletin board over the sofa along the west wall of the third-floor lounge in Boland Hall.

The results of this extensive investigation were presented to a grand jury. In June 2003 the grand jury returned indictments against two Seton Hall students for arson, aggravated assault, reckless manslaughter, and felony murder. The fire investigators and their determination of arson were tested over the next 3-1/2 years in pretrial litigation.

A defense motion was filed challenging the techniques, methodology, and procedures used by investigators in the course of this investigation. After extensive review and examination the trial judge for this case ruled that the investigation into the Seton Hall fire was sound and that it would be admitted into evidence at trial.

On November 15, 2006, Joseph LePore and Sean Ryan, during their allocution at their guilty plea, confessed that they had introduced an open flame to the construction paper that covered the west wall sofa in the third floor lounge. These defendants were sentenced to five years in state prison for arson on January 26, 2007.

Case study courtesy of Gerald Haynes, P.E., Forensic Fire Analysis, LLC, and Michael Morris, Assistant Prosecutor Office of the Essex County Prosecutor. This study was previously published at InterFlam 2007, and reproduced by permission.

Summary

Fire testing includes a very large range of tests, from simple field flammability tests such as *NFPA 705*, to bench-scale fabric tests such as ASTM and *16 CFR* tests, to full-scale tests in buildings. Useful data from such tests can range from simple observations to temperatures and radiant heat fluxes, and owing to oxygen depletion calorimetry, even heat release rates of large fuel packages. Fire tests are often designed, conducted, and analyzed to collect more information about basic fire processes. This information is then published in peer-reviewed publications and authoritative treatises, or on websites. (See the Pearson-Brady Resource Central box.) The data are then available for use in predicting ignition and fire events. Data from such tests can fill a critical role in testing hypotheses about the ignition, spread, and effects of fire.

The criteria for using fire test information in forensic fire scene reconstructions are whether the test was correctly performed, whether the data were accurately collected and reported, and whether the test was appropriate and applicable to the situation under consideration. Fire tests are designed to collect certain data in a reproducible and valid manner. The investigator must ask whether the fuels, conditions, and ignition mechanism reproduced the fire in question. Was the test designed to follow a published test protocol such as one from ASTM or NFPA? If so, did it actually follow that protocol? If not, what factors were considered in its design? What variables were considered and how were they controlled? Fuel moisture, fuel mass and quantity, physical state, ambient temperature and humidity, heat flux, and oxygen content all play important roles in ignition, flame spread, and heat release. If it was a custom-designed test, what data could be fairly and accurately collected and analyzed? Was there a planned series of tests to examine the sensitivity and reproducibility of the data? Because of the importance of fire test data in both criminal and civil fire investigations, it is imperative that tests be conducted and data be interpreted without misrepresentation in a balanced, impartial, and reproducible manner.

Problems

8.1. If the test was intended to replicate an actual event, how closely did the materials, dimensions, and the ventilation match the original conditions?

8.2. Find an example of a commercial, academic, or governmental fire testing facility in your state. Visit or call this organization and determine what type of testing it performs.

8.3. Obtain a collection of at least 10 tests involving the use of a calorimeter from published research.

8.4. Research the methods of conducting field fire testing.

8.5. Obtain small samples of different clothing or upholstery fabrics from a fabric store (with identified content) and conduct *NFPA 705* ignition tests on each (in a safe location). Collect data and compare observations with descriptions included in the references.

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