NFPA® 555

Guide on Methods for Evaluating Potential for Room Flashover

2013 Edition

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An International Codes and Standards Organization

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NFPA® 555

Guide on

Methods for Evaluating Potential for Room Flashover

2013 Edition

This edition of NFPA 555, *Guide on Methods for Evaluating Potential for Room Flashover*, was prepared by the Technical Committee on Hazard and Risk of Contents and Furnishings. It was issued by the Standards Council on May 29, 2012, with an effective date of June 18, 2012, and supersedes all previous editions.

This edition of NFPA 555 was approved as an American National Standard on June 18, 2012.

Origin and Development of NFPA 555

This guide was the first document prepared by the Technical Committee on Hazard and Risk of Contents and Furnishings. It was developed in recognition that life safety and property protection can be enhanced by preventing the occurrence of flashover or, at least, by decreasing its probability.

The 2000 edition represented a reconfirmation of the 1996 edition.

The 2009 edition contained a small addition to Chapter 9 for individual fuel packages, along with minor revisions throughout the document. Annex B was completely revised to provide more up-to-date information on room fire models.

The 2013 edition has added references in Chapter 9 to NFPA 289, *Standard Method of Fire Test for Individual Fuel Packages*, and to NFPA 556, *Guide on Methods for Evaluating Fire Hazard to Occupants of Passenger Road Vehicles*, for use in estimating heat release rates.

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Committee Scope: This Committee shall have primary responsibility for documents on fire hazard calculation procedures for use by other Committees in writing provisions to control the fire hazards of contents and furnishings. This Committee shall also provide guidance and recommendations to Committees in assessing the fire hazard of contents and furnishings. It shall establish classification and rating systems, request the development and standardization of appropriate fire tests, and identify and encourage necessary research as it relates to the fire hazards of contents and furnishings. It shall act in a liaison capacity between NFPA and the committees of other organizations with respect to the hazard of contents and furnishings.

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NOTICE: An asterisk (*) following the number or letter designating a paragraph indicates that explanatory material on the paragraph can be found in Annex A.

Changes other than editorial are indicated by a vertical rule beside the paragraph, table, or figure in which the change occurred. These rules are included as an aid to the user in identifying changes from the previous edition. Where one or more complete paragraphs have been deleted, the deletion is indicated by a bullet (•) between the paragraphs that remain.

A reference in brackets [ ] following a section or paragraph indicates material that has been extracted from another NFPA document. As an aid to the user, the complete title and edition of the source documents for extracts in advisory sections of this document are given in Chapter 2 and those for extracts in the informational sections are given in Annex C. Extracted text may be edited for consistency and style and may include the revision of internal paragraph references and other references as appropriate. Requests for interpretations or revisions of extracted text should be sent to the technical committee responsible for the source document.

Information on referenced publications can be found in Chapter 2 and Annex C.

Chapter 1 Administration

1.1 Scope.

1.1.1 This guide addresses methods for evaluating the potential for room flashover from fire involving the contents, furnishings, and interior finish of a room. The methods addressed by this guide include prevention of ignition; installation of automatic fire suppression systems; control of ventilation factors; and limitation of the heat release rate of individual and grouped room contents, furnishings, and interior finish.

1.1.2 The accuracy, precision, and relevance of this guide are a function of the accuracy, precision, and relevance of the data from the test methods and calculations used. The principles and concepts presented are among the most reliable available. The use of these techniques can help to minimize the probability of flashover or delay its occurrence, but might not prevent it.

1.2 Purpose.

1.2.1 The purpose of this guide is to provide tools for individuals or organizations attempting to implement methods to prevent the occurrence of flashover or, at least, to decrease its probability.

1.2.2 Any limitations on the availability of data, of appropriate test procedures, of adequate fire models, or of state-of-the-art scientific knowledge place significant constraints on the procedures described in this guide.

1.2.3 This guide describes some standard tests conducted under controlled laboratory conditions. Such tests should not be deemed to establish performance levels for all situations.

Chapter 2 Referenced Publications

2.1 General. The documents or portions thereof listed in this chapter are referenced within this guide and should be considered part of the recommendations of this document.

2.2 NFPA Publications. National Fire Protection Association, 1 Batterymarch Park, Quincy, MA 02169-7471.

NFPA 12, *Standard on Carbon Dioxide Extinguishing Systems,* 2011 edition.

NFPA 13, *Standard for the Installation of Sprinkler Systems,* 2013 edition.

NFPA 13D, *Standard for the Installation of Sprinkler Systems in One- and Two-Family Dwellings and Manufactured Homes,* 2013 edition.

NFPA 13R, *Standard for the Installation of Sprinkler Systems in Low-Rise Residential Occupancies,* 2013 edition.

NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protection,* 2012 edition.

NFPA 16, *Standard for the Installation of Foam-Water Sprinkler and Foam-Water Spray Systems,* 2011 edition.

NFPA 17, *Standard for Dry Chemical Extinguishing Systems,* 2009 edition.

NFPA 17A, *Standard for Wet Chemical Extinguishing Systems,* 2009 edition.

NFPA 25, *Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems,* 2011 edition.

NFPA 92, *Standard for Smoke Control Systems,* 2012 edition.

NFPA 204, *Standard for Smoke and Heat Venting,* 2012 edition.

NFPA 265, *Standard Methods of Fire Tests for Evaluating Room Fire Growth Contribution of Textile or Expanded Vinyl Wall Coverings on Full Height Panels and Walls,* 2011 edition.

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NFPA 286, *Standard Methods of Fire Tests for Evaluating Contribution of Wall and Ceiling Interior Finish to Room Fire Growth,* 2011 edition.

NFPA 289, *Standard Method of Fire Test for Individual Fuel Packages,* 2009 edition.

NFPA 556, *Guide on Methods for Evaluating Fire Hazard to Occupants of Passenger Road Vehicles,* 2011 edition.

NFPA 750, *Standard on Water Mist Fire Protection Systems,* 2010 edition.

NFPA 2001, *Standard on Clean Agent Fire Extinguishing Systems,* 2012 edition.

2.3 Other Publications.

2.3.1 ASTM Publications. ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959.

ASTM E 603, *Standard Guide for Room Fire Experiments*, 2007.

ASTM E 1321, *Standard Test Method for Determining Material Ignition and Flame Spread Properties*, 2009.

ASTM E 1354, *Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*, 20011a.

ASTM E 1474, *Standard Test Method for Determining the Heat Release Rate of Upholstered Furniture and Mattress Components or Composites Using a Bench Scale Oxygen Consumption Calorimeter*, 2010.

ASTM E 1537, *Standard Test Method for Fire Testing of Upholstered Furniture*, 2007.

ASTM E 1590, *Standard Test Method for Fire Testing of Mattresses*, 2007.

ASTM E 1740, *Standard Test Method for Determining the Heat Release Rate and Other Fire-Test-Response Characteristics of Wall Covering or Ceiling Covering Composites Using a Cone Calorimeter,* 2010.

ASTM E 1822, *Standard Test Method for Fire Testing of Stacked Chairs,* 2009.

ASTM E 2061, *Guide for Fire Hazard Assessment of Rail Transportation Vehicles,* 2009a.

ASTM E 2067, *Standard Practice for Full-Scale Oxygen Consumption Calorimetry Fire Tests*, 2008.

ASTM E 2257, *Standard Test Method for Room Fire Test of Wall and Ceiling Materials and Assemblies*, 2008.

ASTM E 2280, *Standard Guide for the Fire Hazard Assessment of the Effect of Upholstered Seating Furniture Within Patient Rooms of Health Care Facilities*, 2009.

2.3.2 ISO Publications. International Organization for Standardization, 1, rue de Varembé, Case postale 56, CH-1211 Geneve 20, Switzerland.

ISO 9705, *Fire Tests — Full-Scale Room Tests for Surface Products*, 1993.

2.3.3 SFPE Publications. Society of Fire Protection Engineers, 7315 Wisconsin Avenue, Suite 1225 W, Bethesda, MD 20814.

SFPE Engineering Guide for Assessing Flame Radiation to External Targets from Pool Fires, 1999.

SFPE Engineering Guide to Performance-Based Fire Protection, Second Edition, 2008.

SFPE Engineering Guide to Piloted Ignition of Solid Materials Under Radiant Exposure, 2002.

2.3.4 UL Publications. Underwriters Laboratories Inc., 333 Pfingsten Road, Northbrook, IL 60062-2096.

UL 1975, *Standard for Fire Tests for Foamed Plastics Used for Decorative Purposes*, 2006.

2.3.5 Other Publications.

ACT/DFA, *Flammability Studies of Selected Fabrics, Flame-Blocking Barriers, and Polyurethane Foams in the California Technical Bulletin 133 and Cone Calorimeter Protocols*, Association for Contract Textiles and Decorative Fabrics, Fort Worth, TX, 1995.

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Waksman, D., and Ferguson, J., "Fire Tests of Building Interior Covering Systems," *Fire Technology*, August 1974.

2.4 References for Extracts in Advisory Sections.

NFPA *101*®, *Life Safety Code*®, 2012 edition.

Chapter 3 Definitions

3.1 General. The definitions contained in this chapter apply to the terms used in this guide. Where terms are not defined in this chapter or within another chapter, they should be defined using their ordinarily accepted meanings within the context in which they are used. *Merriam-Webster's Collegiate Dictionary*, 11th edition, is the source for the ordinarily accepted meaning.

3.2 NFPA Official Definitions.

3.2.1 Guide. A document that is advisory or informative in nature and that contains only nonmandatory provisions. A guide may contain mandatory statements such as when a guide can be used, but the document as a whole is not suitable for adoption into law.

3.2.2 Should. Indicates a recommendation or that which is advised but not required.

3.3 General Definitions.

3.3.1 Contents and Furnishings. Any movable objects in a building that normally are secured or otherwise put in place for functional reasons, excluding (1) parts of the internal structure of the building and (2) any items meeting the definition of interior finish. *(See also 3.3.4, Interior Finish.)*

3.3.2* Flashover. A stage in the development of a contained fire in which all exposed surfaces reach ignition temperatures more or less simultaneously and fire spreads rapidly throughout the space.

3.3.3* Fuel Package. A grouping of one or more furnishings or contents items, or both, whose proximity is sufficiently close that the ignition of one item can be expected to cause the spread of fire to the remaining items in the fuel package.

3.3.4* Interior Finish. The exposed surfaces of walls, ceilings, and floors within buildings. [***101*,** 2012]

3.3.5* Item. A single combustible object within the compartment that is permanent or transient, movable, or fixed.

Chapter 4 Instructions for Use of This Guide

4.1 Procedures. This guide is best used with a proper understanding of its various procedures. Its core consists of five chapters that guide the user through analyses and procedures used to determine the likelihood of a compartment under investigation reaching flashover under fire conditions and to minimize the potential for flashover.

4.2 Illustration of Use. Figure 4.2 illustrates the steps for using this guide in the evaluation of the potential for room flashover.

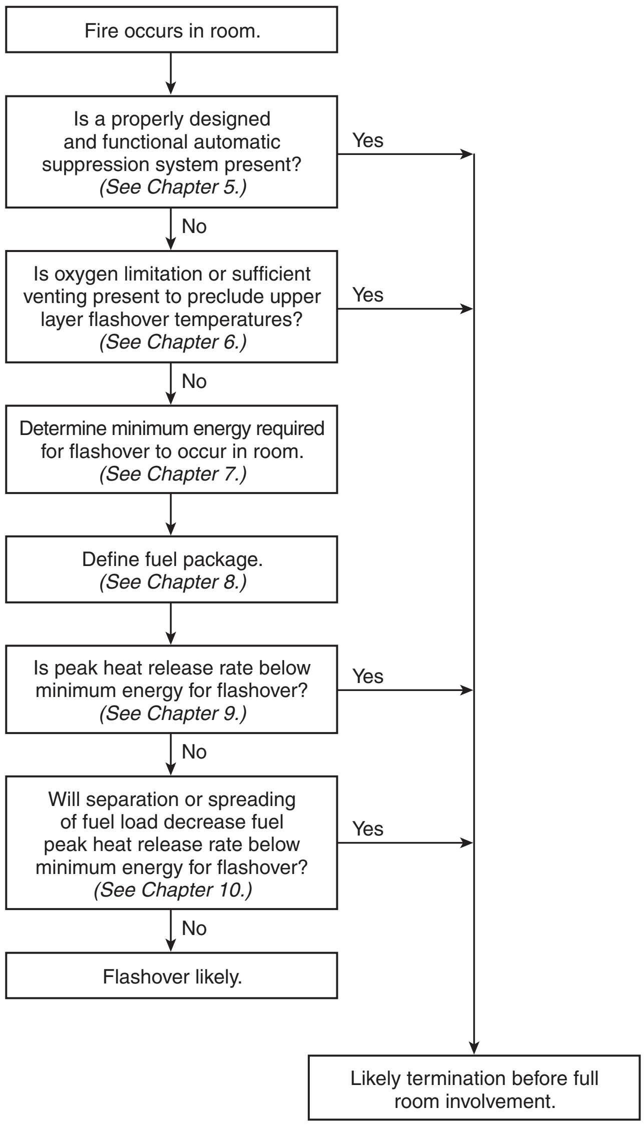


FIGURE 4.2 Flowchart for Use of NFPA 555.

4.3 Analyses. After conducting the analysis provided in each chapter, the user can determine whether the potential for flashover has been decreased sufficiently or whether additional analysis is necessary. However, the user need not necessarily complete the analysis of each chapter before moving on to another.

4.4 Means of Fire Control. The first considerations in the analysis are the means of fire control, either via the existence of a properly designed and functional automatic suppression system or via techniques for smoke venting or reduction in oxygen availability. These issues are addressed in Chapter 4 and Chapter 5, respectively. A properly designed and functional system of either kind is likely to be a satisfactory means of reducing the potential for flashover.

4.5 Conditions for Further Analyses. If either of the following conditions exists, the user should conduct the analysis specified in Chapters 7 through 10:

(1) There is neither a properly designed and functional automatic suppression system nor a similarly adequate method of reduction in oxygen availability.
(2) Added precautions are desired.

4.6 Fuel Packages. Fuel packages should be defined using the concepts in Chapter 8.

4.7 Flashover-Potential Analysis. Chapter 7 contains techniques for predicting flashover in compartments, irrespective of the contents, furnishings, or interior finishes involved. Chapters 8 and 9 indicate how the fire performance of contents, furnishings, or interior finishes can be used to assess the potential for flashover. Chapter 10 explains how the techniques in Chapter 9 can be expanded to include groups of items or products as fuel packages.

4.8* Applications in Codes. The performance-based options commonly included in codes and standards are typical applications where the results of an analysis such as the one performed based on this guide would be useful.

Chapter 5 Automatic Suppression Systems

5.1 General. Automatic suppression systems are the most widely used method for automatically controlling a fire. Consideration should be given to using an automatic suppression system to limit the fire hazard potential in a room in order to reduce the probability of room flashover.

5.2 System Failure. Although automatic suppression systems have an outstanding record of success, it is possible for such systems to fail. Failures are often due to weaknesses in the system that could have been avoided if appropriate attention had been given at the time of design, installation, or inspection. Issues pertaining to system integrity should be addressed carefully to increase the probability of successful operation of a suppression system. If a properly designed and functioning automatic suppression system is used in the design of a room, a fire that occurs in that room is likely to be controlled or extinguished by the suppression system prior to full room involvement (flashover). Figure 5.2 provides a graphic representation of the effect of automatic suppression systems on heat release rate from a fire.

5.3 Hazard Protection. Many standards exist to aid designers in the development of appropriate automatic suppression system design criteria for a wide range of occupancy types and hazards. Because the range and severity of occupancy types and fire types are rather broad, and because protection goals vary from minimal property protection to large-scale life safety, it is essential that hazards be identified and evaluated and that applicable design criteria be employed.

5.4 Evaluation Considerations for Automatic Suppression Systems.

5.4.1 If a recognized design standard is not the basis for a suppression system design or if a unique or innovative suppression system approach is proposed, an evaluation of suppression system capabilities should be considered. Such an approach should include an analysis of the time to activation of the proposed suppression system compared to an evaluation of the "design fire" growth time with respect to the onset of flashover.

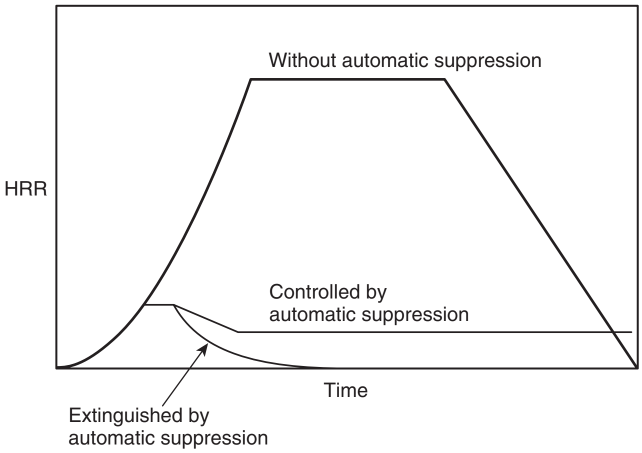


FIGURE 5.2 Effect of Automatic Fire Suppression Systems on Heat Release Rate. ***(Source: SFPE Engineering Guide to Performance-Based Fire Protection, Figure 9–3.)***

5.4.2 Factors that significantly affect an automatic suppression system's ability to prevent flashover include fire growth rate, quantity and arrangement of combustibles, enclosure characteristics, oxygen availability, fire detector (sprinkler) response characteristics, agent application rate (density), agent discharge characteristics, and duration of agent supply. Depending on the circumstances of the hazard and the level of protection required, some or all of the preceding factors might have to be evaluated to establish confidence in an automatic suppression system's ability to reduce the probability of flashover significantly.

5.5 Design, Installation, and Maintenance. The design, installation, and maintenance of automatic suppression systems are covered by a number of NFPA standards, including the following:

(1) NFPA 12, *Standard on Carbon Dioxide Extinguishing Systems*
(2) NFPA 13, *Standard for the Installation of Sprinkler Systems*
(3) NFPA 13D, *Standard for the Installation of Sprinkler Systems in One- and Two-Family Dwellings and Manufactured Homes*
(4) NFPA 13R, *Standard for the Installation of Sprinkler Systems in Low-Rise Residential Occupancies*
(5) NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protection*
(6) NFPA 16, *Standard for the Installation of Foam-Water Sprinkler and Foam-Water Spray Systems*
(7) NFPA 17, *Standard for Dry Chemical Extinguishing Systems*
(8) NFPA 17A, *Standard for Wet Chemical Extinguishing Systems*
(9) NFPA 25, *Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems*
(10) NFPA 750, *Standard on Water Mist Fire Protection Systems*
(11) NFPA 2001, *Standard on Clean Agent Fire Extinguishing Systems*

Chapter 6 Oxygen Availability and Ventilation

6.1 Considerations. Oxygen availability or ventilation parameters can play a significant role in fire growth, the combustion process, and conditions that influence flashover potential in various types of fire scenarios.

6.1.1 Typical Fire Scenarios. Normal air contains 20.9 percent oxygen, 79.1 percent nitrogen, and traces of other gases. In the combustion process, fuel combines with oxygen in air, and the size of a resulting fire can be limited by the amount of either fuel or oxygen available for the combustion process. In most common fire scenarios, it should be reasonable to assume that oxygen is supplied to the fire from the surrounding air and that sufficient ventilation or air leakage paths are present to allow a continued supply of air and oxygen. The continued availability of air allows the growth of fire and the continued burning of contents, furnishings, or interior finishes in a compartment.

6.1.2 Tightly Closed Compartments. In fire scenarios in which a compartment is tightly closed or lacks sufficient ventilation or air leakage paths, the available oxygen is consumed in the combustion process until the oxygen volume concentration is reduced to between 8 percent and 12 percent. At these reduced oxygen levels, the flaming combustion of contents, furnishings, or interior finishes in a compartment can cease, and the remaining oxygen will not be consumed. These conditions can prevent the fire from growing to a size sufficient to produce flashover conditions. However, a sudden introduction of air (and oxygen) can result in a highly dangerous, rapid combustion of products of incomplete combustion, called a *backdraft.* A backdraft might occur when doors are opened or windows are broken in the process of manual fire fighting.

6.1.3 Vented Scenarios. In some fire scenarios, there is an abundance of ventilation in the form of a smoke/heat venting means or other exhaust mechanism that relieves sufficient heat and gases from a compartment, precluding the temperature rise conditions necessary to induce flashover (Hinkley, 1988).

6.2 Oxygen Consumption.

6.2.1 Principle of Oxygen Consumption. A determination has been made that the heat released per unit mass of oxygen consumed is nearly constant for most organic fuels. In air-limited fire scenarios, this value can be useful in determining whether the fire duration or maximum heat release rate predicted to cause flashover can be achieved. The value of heat released per unit mass of oxygen consumed is 13.1 kJ/g (on an oxygen basis). The value of heat released per unit volume of oxygen consumed, $\Delta h_c \times \rho_{O_2}$, is 18.7×10^3 kJ/m^3 (on an oxygen basis), at 0°C. The corresponding values on an air basis are 3 kJ/g and 3.9×10^3 kJ/m^3 (also at 0°C).

6.2.2 Tightly Closed Compartments.

6.2.2.1 In tightly closed compartments, flashover potential exists only if the heat released by the fire can exceed the heat release rate necessary for flashover using the oxygen supply available in the compartment.

6.2.2.2 The duration of burning in a tightly closed compartment can be estimated for steady fires and for unsteady fires in which the heat release rate grows proportionally to the square of time (*t*-square fires). Estimations are based on the volume of the space and the heat release rate as shown in Equation (6.2.2.2a) for steady fires and Equation (6.2.2.2b) for unsteady (*t*-square) fires.

$$t = \frac{V_{O_2}}{\dot{Q}}\left(\Delta h_c \times \rho_{O_2}\right) \tag{6.2.2.2a}$$

$$t=\left[\frac{3V_{O_2}}{\alpha}\left(\Delta h_c\times\rho_{O_2}\right)\right]^{1/3} \quad \textbf{(6.2.2.2b)}$$

where:

t = time (sec)
V_{O_2} = volume of oxygen available to be consumed in combustion process *[see 6.2.2.3]* (m^3)
$\Delta h_c \times \rho_{O_2}$ = heat release per unit volume of oxygen consumed (kJ/m^3)
$\dot{Q}$ = heat release rate from steady fire (kW)
α = constant governing the speed of fire growth (kJ/sec^3)

6.2.2.2.1 Values of α for typical fire growths are as shown in Table 6.2.2.2.1.

Table 6.2.2.2.1 Values of α

Speed of Fire	SI Units	U.S. Customary Units
Slow	2.93×10^{-3} kJ/sec^3	0.00278 Btu/sec^3
Medium	11.72×10^{-3} kJ/sec^3	0.01111 Btu/sec^3
Fast	46.88×10^{-3} kJ/sec^3	0.04444 Btu/sec^3

6.2.2.2.2 The maximum heat release rate for the unsteady (t-square) fire can be estimated as follows in Equation 6.2.2.2.2, where t is the time, as determined from Equation 6.2.2.2b:

$$Q=\alpha t^2 \quad \textbf{(6.2.2.2.2)}$$

6.2.2.2.3 The equations consider the energy associated with the mass (or volume) of oxygen consumed in the compartment, and the energy is divided by the anticipated heat release rate of the fire.

6.2.2.3 It can be estimated that the maximum volume of oxygen available to be consumed in the combustion process is approximately half of the total available oxygen, since flaming combustion usually is not sustained once oxygen concentrations fall to the range of 8 percent to 12 percent.

6.2.3 Temperature Rise in Compartment.

6.2.3.1 With the times of fire duration determined from Equations 6.2.2.2a and 6.2.2.2b, Equation 6.2.3.1, based on the compartment volume (containing air as an ideal gas at constant pressure with constant specific heat), can be used to estimate the temperature rise in the compartment and to determine whether temperature conditions are sufficient for flashover (Milke and Mowrer, 1993).

$$\Delta T = T_0\left[\exp\left(Q_n/Q_0\right)-1\right] \quad \textbf{(6.2.3.1)}$$

6.2.3.2 In Equation 6.2.3.1, Q_n is the net total heat released, which can be determined from Equation 6.2.3.2a or Equation 6.2.3.2b, depending on the type of fire, and Q_0 is the total ambient energy of air in the compartment, calculated using Equation 6.2.3.2c.

$$Q_n=\left(1-X_L\right)\dot{Q}\left(\Delta t\right) \quad \text{(steady fires)} \quad \textbf{(6.2.3.2a)}$$

$$Q_n=\left(1-X_L\right)\frac{\alpha t^3}{3} \quad \text{[unsteady (t-square) fires]} \quad \textbf{(6.2.3.2b)}$$

$$Q_0=\rho_0 c_p T_0 V \quad \textbf{(6.2.3.2c)}$$

6.2.3.3 The terms used in Equations 6.2.3.1, 6.2.3.2a, 6.2.3.2b, and 6.2.3.2c are described as follows:

X_L = fraction of heat loss to compartment boundaries (typical range, 0.6 to 0.95)
$\dot{Q}$ = heat release rate of the fire (kW)
α = a constant governing the speed of fire growth (kJ/sec^3)
Δt = time period (sec)
ρ_0 = density of air (kg/m^3)
c_p = specific heat of air [kJ/(kg K)]
T_0 = initial air temperature (K)
V = volume of air in compartment (m^3)

6.2.4* Other than the method of analysis outlined using the equations in 6.2.2.2 through 6.2.3.3, there are computer-based models that can evaluate the oxygen depletion, ventilation, and heat transfer effects that impact the flashover potential in tightly closed compartments.

6.3 Venting and Exhaust of Hot Smoke Layer.

6.3.1 Smoke produced from a flaming fire in a space is assumed to be buoyant, rising in a plume above the fire and striking the ceiling or stratifying due to temperature inversion. The space can be expected to begin to fill with smoke, with the smoke layer interface descending. The descent rate of the smoke layer interface depends on the rate at which smoke is supplied to the smoke layer from the plume. This scenario assumes a two-zone model in which there is a distinct interface between the bottom of the smoke layer and the ambient air. For engineering purposes, the smoke supply rate from the plume can be estimated to be the air entrainment rate into the plume below the smoke layer interface.

6.3.2 The heat that is convected upward into the space or compartment results in an increase in temperature in the smoke layer in the space. The provision of vents or mechanical means of exhaust can serve to remove the hot gases from the rising fire plume, which increases the amount of air entrainment and promotes a lower smoke layer temperature. With appropriate consideration given to the amount of venting or exhaust and the expected fire size, the compartment smoke layer gas temperatures can be limited below the 600°C threshold indicator for flashover. Additional guidance and calculation methods can be found in NFPA 92, *Standard for Smoke Control Systems*, and NFPA 204, *Standard for Smoke and Heat Venting*.

Chapter 7 Predicting Flashover for Fire Hazard Calculations

7.1 Background.

7.1.1 General. The occurrence of flashover within a room is the ultimate signal of untenable conditions within the room of fire origin as well as a sign of greatly increased risk to other rooms within the building. A number of experimental studies of full-scale fires have been performed that provide an adequate but imprecise definition of flashover in terms of measurable physical properties. Computer simulations of the growth of a fire within a room are available.

7.1.2* Temperature. Temperature rise in the upper layer of a compartment has been used as a criterion for indication of flashover. Documentation indicates that a gas temperature rise at flashover of 600°C is a reasonable expectation.

7.1.3* Heat Flux. Heat flux at floor level also has been used as a criterion for indication of flashover. Documentation indicates that a heat flux at floor level at flashover of 20 kW/m^2 is a reasonable expectation.

7.2 Estimating Room Flashover Potential.

7.2.1* Room flashover potential is best estimated by using Thomas's flashover correlation (Thomas, 1981), as provided in Equation 7.2.1a. The constants in Equation 7.2.1a represent values correlated to experiments that produce flashover.

$$\dot{Q} = 7.8A_{room} + 378\left(A_{vent}\sqrt{H_{vent}}\right)_{equivalent} \quad \textbf{(7.2.1a)}$$

$$A_{room} = A_{floor} + A_{ceiling} + A_{walls} - \left(A_{vents}\right)_{equivalent} \quad \textbf{(7.2.1b)}$$

$$W_{vent\ equivalent} = \frac{\sum_{i=1}^{n}\left(A_{vent}\sqrt{H_{vent}}\right)i}{\sqrt{H^3_{vent\ equivalent}}} \quad \textbf{(7.2.1c)}$$

where:

$\dot{Q}$ = heat release rate of the fire (kW)

A_{vent} = H_{vent} W_{vent} (m^2) in which the product, H_{vent} W_{vent}, represents the dimensions of an equivalent vent defined by Equation 7.2.1a

$H_{vent\ equivalent}$ = difference between the elevation of the highest point among all of the vents and the elevation of the lowest point among all of the vents (m)

$W_{vent\ equivalent}$ = width of a virtual vent that has an area equivalent (for the purposes of determining flashover) to the combined area of all individual vents from the room of consideration (m)

7.2.2* Alternative methods of estimating heat release at flashover also have been reported (Babrauskas, 1980a; Babrauskas and Krasny, 1985; McCaffrey et al., 1981; Quintiere, 1982; Deal and Beyler, 1990). A review of techniques for predicting flashover has been conducted (Peacock et al., 1999).

7.2.3* General Information on Thomas's Correlation.

7.2.3.1 The formulation of the energy balance considered only the heat losses from the hot gas layer and heated walls to the cooler lower walls and floor surfaces. The term A_{room} actually should include all surfaces inside the room, exclusive of the vent area.

7.2.3.2 The fire area should not be subtracted from the floor area, because the fire conducts and convects heat into the floor underneath the fuel footprint.

7.2.3.3 Equation 7.2.1a is not dependent on the location or form of the vent (a window or a door); however, the equation was developed from tests where venting was through a window as well as a door.

7.2.3.4 Equation 7.2.1a does not address the external insulation of the walls. Thus, using the equation for compartments with thin metal walls might be inappropriate.

7.2.3.5 Equation 7.2.1a was developed from tests using fast-growth fires and has not been verified for fires that grow slowly or at moderate rates.

7.2.3.6 Equation 7.2.1a was developed from experiments conducted in rooms not exceeding 16 m^2 in floor area. Extrapolation of the results from this equation for application to rooms with much larger floor areas might not be valid.

7.2.3.7 Equation 7.2.1a is not valid for compartments without ventilation, because it would predict the possibility of flashover, which would be unlikely due to oxygen starvation of the fire.

7.2.3.8 The experiments used to develop this equation included the use of compartments with thermally thick walls and wood crib fires. The validity of the equation was later confirmed in gypsum-lined rooms using furniture fires (Parker and Lee, 1973). Its validity for other surfaces or fire sources has not been fully established.

Chapter 8 Fuel Package Definition

8.1 Introduction. This chapter describes methods for defining a fuel package for use in predicting heat release rates, compartment temperatures, and flashover potential.

8.2 Fuel Package. The two aspects of fuel packages that are discussed in this chapter are the definition of a fuel package and the ignition of a fuel package due to heating by another fuel package within the compartment.

8.3 Defining Fuel Packages.

8.3.1 Guidance. This section includes some simple definitions of fuel packages. These definitions should be used for guidance rather than as strict definitions.

8.3.2 Proximity. Objects that are close enough in physical proximity so that continuous flame spread from item to item is possible generally are considered to be a fuel package. In such a situation, the ignition delays associated with object-to-object spread do not dominate the heat release rate history.

8.3.2.1 Items that are so far away from other items or fuel packages that they cannot be ignited by heat transfer from other items or fuel packages are not considered a part of a fuel package.

8.3.2.2 Items that are near enough to other items or fuel packages that ignition of an item is possible due to heat transfer from other items or fuel packages are not included as part of a fuel package if any of the following apply:

(1) The ignition delay is sufficiently long that the peak heat release rate will have passed before the item reaches its peak burning rate.
(2) The methods of Chapter 8 cannot be reasonably used if the item is included as part of a nearby fuel package.
(3) Both 8.3.2.2(1) and 8.3.2.2(2) apply.

Chapter 9 Estimation Techniques for Heat Release Rate

9.1* Introduction. This chapter presents techniques for estimating the heat release rate for various individual items or products in a compartment, based on the results of direct measurements. Heat release rate is a crucial property for assessing fire safety, because its maximum value is the numerical representation of the peak intensity of a fire. Therefore, estimates of heat release rate are critical in predicting whether flashover can occur in a compartment, based on the items or products contained in the compartment and the distances between them. Sections 9.2 through 9.8 present a hierarchy of the preferred techniques for such estimates. The following guidance documents issued by standards-making organizations will be of assistance to anyone considering methods for evaluating potential for flashover:

(1) ASTM E 2061, *Guide for Fire Hazard Assessment of Rail Transportation Vehicles*, investigates fire hazard assessment in a specific occupancy, such as a rail transportation vehicle, which is one type of compartment.
(2) ASTM E 2280, *Standard Guide for the Fire Hazard Assessment of the Effect of Upholstered Seating Furniture Within Patient Rooms of Health Care Facilities*, investigates fire hazard assessment of a specific product, such as upholstered furniture in a patient room of a health care occupancy.
(3) NFPA 556, *Guide on Methods for Evaluating Fire Hazard to Occupants of Passenger Road Vehicles*, investigates the use of such techniques, as well as others, to evaluate and lower fire hazard in passenger road vehicles, such as cars.

9.2 Preferred Hierarchical Order. The preferred hierarchical order indicates that the reliability of results is likely to decrease as the order of technique descends from the optimal to other types. Tests on individual materials and comparative estimates are the techniques with the lowest reliability for assessing the potential for room flashover. The optimal technique is a full compartment test that includes items or products contained in the compartment, with the distances between items and products identical to those in the compartment of interest. The applicable techniques are described in more detail in Sections 9.3 through 9.8. The preferred hierarchical order is as follows:

(1) A full compartment fire test, including all items expected to be contained within the compartment
(2) Full-scale fire tests on individual items
(3) Tests on large-scale mock-ups of individual items
(4) Bench-scale tests, using composite samples representative of the end-use composite assemblies
(5) Bench-scale tests using individual materials rather than composites as samples
(6) Use of estimation techniques for calculating heat release rate in the compartment as determined from the results of tests in 9.2(1) through 9.2(5). This might be done by one of the following:
    (a) Quantitative estimation techniques
    (b) Relative estimation techniques

9.3 Full-Compartment Fire Tests.

9.3.1 Ideally, the heat release rate from the combination of contents, furnishings, and interior finishes contained in a compartment is obtained by carrying out a full compartment fire test, wherein each major combustible item, product, or fuel package is included, replicating as much as possible the locations where the items are to be placed in the compartment under investigation. ASTM E 603, *Standard Guide for Room Fire Experiments*, provides proper guidance for the various choices that should be made. These include information on operator safety and on the most appropriate experimental techniques for various measurements. This approach is best suited for cases where multiple compartments with very similar contents and distributions are to be constructed. ASTM E 2067, *Standard Practice for Full-Scale Oxygen Consumption Calorimetry Fire Tests*, describes the methods to construct, calibrate, and use full-scale oxygen consumption calorimeters to help minimize testing result discrepancies between laboratories. The ASTM E 2067 practice goes beyond standardized test methods in discussing the conduction of different types of tests, including some in which the objective is to assess comparatively the fire performance of products releasing low amounts of heat or smoke and some in which the objective is to assess whether flashover will occur. It also describes the equations required for calculations of heat and smoke release.

9.3.2 One of the most important issues that needs to be addressed by the designer of a full-scale test is the selection of an ignition source.

9.3.2.1 If the only objective is to ensure that flashover cannot occur with the existing combustible contents, the size of the ignition source used is of little importance as long as it is not large enough to cause flashover on its own. An initial test should be carried out, with the ignition source as the only item present, to confirm that flashover does not occur in the absence of other combustible items. The objective of this test is extremely limited.

9.3.2.2 If the experiment is being carried out to determine the fire hazard inherent in the compartment being considered, the choices of ignition source and its location are crucial to the results of the test. They should be chosen to represent a realistic fire source in the occupancy under investigation.

9.3.2.3 If the experiment is being carried out in order to make a decision between various types of items or fuel packages of a particular type (e.g., an upholstered chair or a mattress), the ignition source should be sufficiently large to be a realistic fire source but small enough so that total consumption of the item is not inevitable. Therefore, the ignition source for such a full-scale test should not be so large as to overwhelm the product, irrespective of its fire performance.

9.3.3 Disadvantages to carrying out full compartment fire tests include the following:

(1) They are costly, both in terms of actual expense and in terms of preparation.
(2) They are less susceptible to generalization, because small differences in item or fuel package location can have major effects on fire performance.
(3) They cannot easily identify the effects of individual items or fuel packages on the overall fire performance of the whole compartment.

9.3.4 The ultimate objective of the tests should be to determine whether the compartment, as configured, is expected to reach flashover. If flashover is not reached, the results can be used for comparisons between items or products with similar functions but differing construction or materials. Results from tests that do not reach flashover should be compared with the calculated heat release rates necessary for flashover or the upper gas layer temperatures necessary for flashover. The potential for flashover should be assessed in light of the reproducibility of test results and the impact of test result variability on achieving flashover conditions.

9.4 Full-Scale Tests on Individual Items or Fuel Packages.

9.4.1 General.

9.4.1.1 Full-scale tests have been developed for a variety of individual items, including wall finish, upholstered furniture, and mattresses. Full-scale tests also can be conducted on individual fuel packages in the same way in which they are conducted for individual items. The choices of ignition source and location are crucial to the results of the test. They should be chosen to represent a realistic fire source in the occupancy under investigation.

9.4.1.2* If it is possible that items or fuel packages could deteriorate through normal use or special situations, such as vandalism, additional tests might be necessary to evaluate the items after a suitable period of use or after the occurrence of such special situations (e.g., slashed cover and barrier).

9.4.1.3* If quantitative precision or bias statements have not been developed for the full-scale tests used, compensation should be made for the lack of information regarding precision or bias.

9.4.1.4 Aesthetic design as well as geometric and spatial configuration can have significant influence on the ignition and burning properties of all items used for room contents, furnishings, and interior finishes. The issues of design, geometry, and spatial configuration are far too complex, important, and detailed to cover in this document. The references contained in Chapter 2 and Annex C provide resources on these subjects.

9.4.1.5* The number of material combinations that can be used in the construction of room furnishings is almost infinite. Heat release rate values for each of the composite items are likely to vary significantly and unpredictably from one composite type to another. Component materials can produce significantly differing heat release values, depending on the presence of the other materials and on the physical design or geometry of the item. Thus, the value of design rules of thumb is limited and does not guarantee low rate of heat release values. Product testing therefore is necessary to determine the heat release rate for any given item.

9.4.2* Wall Finish. Full-scale fire performance of wall finishes can be tested by means of NFPA 286, *Standard Methods of Fire Tests for Evaluating Contribution of Wall and Ceiling Interior Finish to Room Fire Growth*, NFPA 265, *Standard Methods of Fire Tests for Evaluating Room Fire Growth Contribution of Textile or Expanded Vinyl Wall Coverings on Full Height Panels and Walls*, ASTM E 2257, *Standard Test Method for Room Fire Test of Wall and Ceiling Materials and Assemblies*, or ISO 9705, *Fire Tests — Full Scale Room Tests for Surface Products.* NFPA 286 is intended to assess heat release and smoke release from interior finish products, with the exception of textile wall coverings, and it applies to wall and ceiling finishes. The reason for its broader applicability than NFPA 265 is that its ignition source is sufficiently large (160 kW, after 5 minutes of test, with the burner flush against the corner) that it generates flames that reach the ceiling of the standard room.

9.4.3 Upholstered Furniture.

9.4.3.1 Full-scale fire performance of upholstered furniture can be tested by means of ASTM E 1537, *Standard Test Method for Fire Testing of Upholstered Furniture.*

9.4.3.2 Models exist that allow the effects of reradiation from room walls on heat release rate to be added to the results of the tests carried out in a furniture calorimeter. These effects are negligible unless the peak heat release rate of the furniture item exceeds 600 kW if tested in a furniture calorimeter or in a room of dimensions ranging from 2.5 m × 3.7 m to 3.1 m × 3.7 m, with a height of 2.5 m. If the heat release rate is that high, the importance of minor effects is probably of little consequence in a flashover prevention strategy (Parker et al., 1990).

9.4.4* Mattresses.

9.4.4.1 Full-scale fire performance of mattresses can be tested by means of ASTM E 1590, *Standard Test Method for Fire Testing of Mattresses.*

9.4.4.2 Models exist that allow the effects of reradiation from room walls on heat release rate to be added to the results of the tests carried out in a furniture calorimeter. These effects are negligible unless the peak heat release rate of the mattress exceeds 600 kW if tested in a furniture calorimeter or in a room of dimensions ranging from 2.5 m × 3.7 m to 3.1 m × 3.7 m, with a height of 2.5 m. If the heat release rate is that high, the importance of minor effects is probably of little consequence in a flashover prevention strategy.

9.4.5 Stacked Chairs.

9.4.5.1 Full-scale fire performance of upholstered furniture can be tested by means of ASTM E 1822, *Standard Test Method for Fire Testing of Stacked Chairs.*

9.4.5.2 The concepts discussed for upholstered furniture and for mattresses also apply to stacked chairs. However, it is important to note that the accelerating effect of stacking combustibles will result in a significantly larger heat release from a stack of combustibles than from the same combustibles placed side by side. Studies on the heat release of stacked chairs (Hirschler and Treviño, 1997) have shown that self-propagating fires (which are likely to lead to flashover if sufficient combustibles are present) can result from stacking individual chairs, each one of which generates low heat release.

9.4.6 Other Items.

9.4.6.1 Full-scale fire performance testing of other items should be performed by designing specialized tests for the item under consideration. Similar types of criteria related to the documents referenced in 9.4.2, 9.4.3, 9.4.4, and Section 9.5 should be developed. Items or fuel packages of potential interest include pallets of storage commodities, case goods, and cleaning supplies.

9.4.6.2 It is recommended that ASTM E 603, *Standard Guide for Room Fire Experiments*, and ASTM E 2067, *Standard Practice for Full-Scale Oxygen Consumption Calorimetry Fire Tests*, be used as sources of information for developing the test and for making the measurements.

9.4.6.3 Currently, no standard full-scale fire test exists for floor finish *(see A.9.6.4)*. In general, floor finish is not involved in fires until flashover is approached.

9.4.6.4 Furniture calorimeter test methods are useful techniques to assess the heat release and other fire properties of individual fuel packages. UL 1975, *Standard for Fire Tests for Foamed Plastics Used for Decorative Purposes*, is intended to assess the heat release and rate of fire development of products containing foamed plastics to be used for displays, stage settings, and other decorative applications. It uses a 340 g wood crib as the ignition source. More recently, NFPA 289, *Standard Method of Fire Test for Individual Fuel Packages*, was developed as a furniture calorimeter test, which uses several gas burner ignition sources at incident gas levels of 20 kW, 40 kW, 70 kW, 100 kW, 160 kW, and 300 kW, to expose individual fuel packages.

9.4.6.5 Individual Fuel Packages.

9.4.6.5.1 The contribution of an individual fuel package to fire growth can be determined by product calorimeter fire test methods. NFPA 289, *Standard Method of Fire Test for Individual Fuel Packages*, should be used for fire testing and general ranking of individual fuel package materials and decorative objects.

9.4.6.5.2* The individual fuel package, in its intended form and orientation, is positioned on a load cell and is exposed to and ignited by a gas burner with a heat output representative of the type of individual fuel package and its intended application. It is recommended that the individual fuel package be exposed to various ignition sources to assess the potential for the fuel package to cause flashover in the end-use application. Typical heat output levels used in product calorimeter fire test methods include 20 kW, 40 kW, 70 kW, 100 kW, 160 kW, and 300 kW, with exposures for 15 minutes.

9.4.6.5.3 A full description of the fuel package and time history profile of the quantitative test data should be reported (heat release, smoke release, mass loss, and combustion product release). A qualitative description of individual fuel package performances should also include the following:

(1) Flame spread on or within the individual fuel package during exposure
(2) Presence of falling debris or burning droplets on the protective barrier that persist in burning for 30 seconds or more
(3) Visibility information in the fire test area
(4) Other pertinent details with respect to fire growth
(5) Falling debris or melting or dripping of materials

9.4.7 Advantages and Disadvantages. The use of tests on individual items has both advantages and disadvantages over testing all components of a compartment.

9.4.7.1 The advantages of testing individual items include the following:

(1) Lower cost
(2) Greater specificity on the individual importance of the item under test
(3) Easier identification of the effects of composition or construction of the item under test on anticipated fire performance

9.4.7.2 The major disadvantage of testing individual items is that the test is incapable of identifying the effect of the item being tested on the remaining items in the compartment.

9.4.8 Assessing Results. To assess whether the compartment, as configured, is likely to reach flashover, tests should be carried out on all major items and the results combined. The simplest way to combine the results is to add the peak heat release rates obtained from the individual items and to compare them with the predicted heat release rate necessary for flashover as determined from Chapter 7. This method can be improved by combining the concept of ignition of "second" items due to the radiation from burning items, based on the ignition propensity of each item and the distance between them (Babrauskas, 1981–82) *(see also 10.3.3)*. A further improvement involves the use of an applicable modeling technique, incorporating experimental fire test data, to predict the potential interactions between the burning items.

9.5 Tests on Large-Scale Mock-Ups of Individual Items.

9.5.1 The effects of product composition on fire performance can be predicted to a considerable extent by carrying out large-scale fire tests on mock-ups of individual items *(e.g., for upholstered furniture, see ASTM E 1537, Standard Test Method for Fire Testing of Upholstered Furniture)*. Such tests should be done in the same way as the tests on full-scale products.

9.5.2 This technique does not provide the investigator with an understanding of the effects of construction on fire performance.

9.5.3 For tests of upholstered furniture, it has been suggested that fire performance predictions can be improved by including factors associated with the mass, the type of frame, and the style of construction (Babrauskas, 1979, 1980b, 1983; Ames et al., 1992; Krasny et al., 2001). All of the aforementioned variables have important effects on heat release; insufficient quantitative information exists to allow estimates of the full-scale effects to be made.

9.5.4 Such testing should not be confused with testing on small-scale mock-ups, which very often is unsatisfactory because the effects of radiation from the flame are missing.

9.6 Bench-Scale Tests on Composite Samples.

9.6.1 General. Heat release and other fire test response characteristics of upholstered furniture or mattress composites in bench scale can be determined by using an application of the cone calorimeter (ASTM E 1354, *Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*), as specified in ASTM E 1474, *Standard Test Method for Determining the Heat Release Rate of Upholstered Furniture and Mattress Components or Composites Using a Bench Scale Oxygen Consumption Calorimeter*, at an incident radiant heat flux of 35 kW/m^2.

9.6.1.1 It is more critical to predict a full-scale heat release rate that is consistent with an inability to escape safely (Sundstrom, 1995) rather than use a regulatory pass/fail criterion, which may be arbitrary. A number of studies attempting to relate test results from bench-scale tests to fire performance in full-scale tests have been conducted, and some of these are discussed in 9.6.1.2 through 9.6.1.9. The peak heat release rate and the average (3-minute) heat release rate of furniture composites in the cone calorimeter (ASTM E 1354, *Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*) can be used to determine whether or not the composite, if used in an actual chair configuration, will lead to a self-propagating fire, thus increasing the potential for flashover. It is important to note that the data published to date have failed to show consistent correlation between bench-scale and full-scale testing for fire test response characteristics.

9.6.1.2 Estimations have been made of peak heat release rate data in the full-scale furniture fire test specified in ASTM E 1537, *Standard Test Method for Fire Testing of Upholstered Furniture*, based on the cone calorimeter (ASTM E 1474, *Standard Test Method for Determining the Heat Release Rate of Upholstered Furniture and Mattress Components or Composites Using a Bench Scale Oxygen Consumption Calorimeter*). The initial work, done cooperatively by NIST and the California Bureau of Home Furnishing and illustrated in Figure 9.6.1.2, suggested that the average (3-minute) heat release rate is capable of predicting full-scale peak heat release rate. Figure 9.6.1.2 compares the average rates of heat release obtained from the cone calorimeter (ASTM E 1354, *Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*) at an incident flux of 35 kW/m^2 with the full-scale test (ASTM E 1537, *Standard Test Method for Fire Testing of Upholstered Furniture*) peak rates of heat release. The work suggested that there is a threshold at approximately 100 kW/m^2, so that systems that generated values below this threshold are not likely to develop self-propagating fires when they are made into actual furniture. Similarly, it suggested that average heat release rate values above 200 kW/m^2 are likely to result in furniture that can cause self-propagating fires. The following equation determines the non-self-propagating fire region found by that study as follows:

$$\dot{Q}(\text{full scale}) = 0.75 \times \dot{Q}''$$

where:

$\dot{Q}$ (full scale) = peak rate of heat release in ASTM E 1537 (kW)

$\dot{Q}''$ = average (3-minute) heat release rate per unit area in ASTM E 1474, *Standard Test Method for Determining the Heat Release Rate of Upholstered Furniture and Mattress Components or Composites Using a Bench Scale Oxygen Consumption Calorimeter*, at an incident flux of 35 kW/m^2 (Parker et al., 1990)

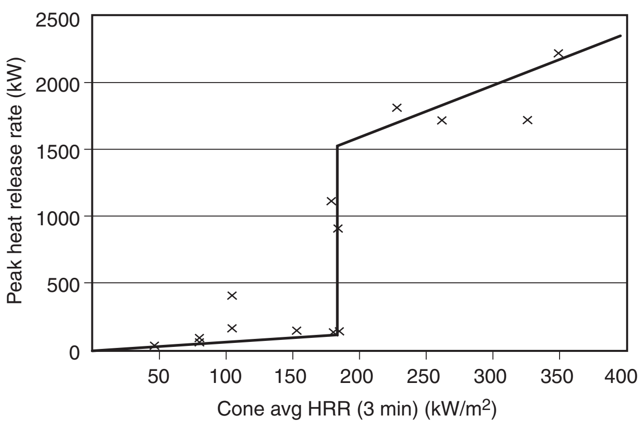


FIGURE 9.6.1.2 Relation of the Results of Full-Scale Upholstered Furniture Tests with the Average Rate of Heat Release from the Cone Calorimeter.

9.6.1.3 Another series of tests were carried out in which nine chairs were tested in ASTM E 1537, *Standard Test Method for Fire Testing of Upholstered Furniture*, and the systems were tested in the cone calorimeter (although not following the procedure in ASTM E 1474, *Standard Test Method for Determining the Heat Release Rate of Upholstered Furniture and Mattress Components or Composites Using a Bench Scale Oxygen Consumption Calorimeter*). All systems had the same foam, interliner, and chair construction but used different fabrics. Figure 9.6.1.3 shows the relationship of the results of one series of full-scale (ASTM E 1537, *Standard Test Method for Fire Testing of Upholstered Furniture*) upholstered furniture tests with the peak rate of heat release from the cone calorimeter (ASTM E 1354, *Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*), at an incident flux of 35 kW/m^2. It illustrates a linear relationship between the peak (not average) heat release rate in the cone and the peak heat release rate in the full-scale test, with a regression correlation coefficient of 86 percent from the results of that study (Hirschler, 1995).

9.6.1.4 It was also estimated that, if the 3-minute average heat release rate in the cone calorimeter was under 160 kW/m^2, the composite, when made into a standard mock-up upholstered furniture item, would be very unlikely to lead to a self-propagating fire (Hirschler, 1999). The cone calorimeter was not being used, in this regard, as a direct predictor of full-scale heat release rate, but rather as an indicator of the probability of a composite to be made into an item of upholstered furniture with good fire performance. The results of this approach suggested that there is a "zone" (with low cone average heat release rate and low standard mock-up peak heat release rate) for which furniture upholstery systems are likely to lead to safer constructions, within a reasonable probability.

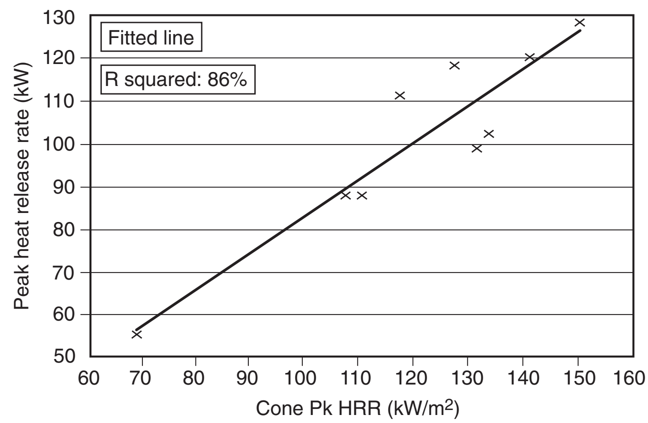


FIGURE 9.6.1.3 One Series of Full-Scale Upholstered Furniture Tests with the Peak Rate of Heat Release from the Cone Calorimeter.

9.6.1.5 It should be stated, however, that such estimations are heavily dependent on the systems tested. Figure 9.6.1.5 shows the relationship of the results of three series of full-scale (ASTM E 1537, *Standard Test Method for Fire Testing of Upholstered Furniture*) upholstered furniture tests with the peak rate of heat release from the cone calorimeter (ASTM E 1354, *Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*), at an incident flux of 35 kW/m^2, and with correlation coefficients of 86 percent, 77 percent, and 73 percent. It indicates that, for three separate series of tests, the regressions found, although all linear, corresponded to different linear equations (Hirschler, 1995).

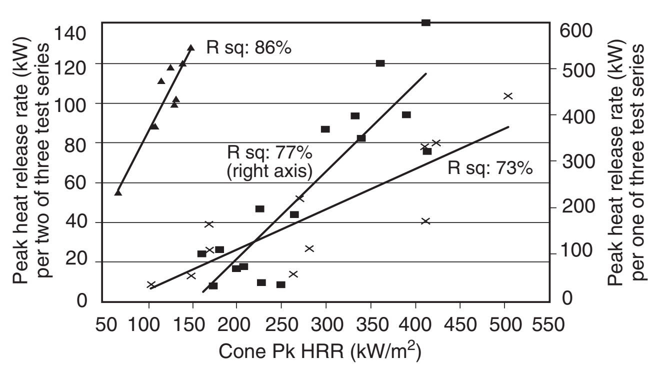


FIGURE 9.6.1.5 Three Series of Full-Scale Upholstered Furniture Tests with the Peak Rate of Heat Release from the Cone Calorimeter.

9.6.1.6 Other studies have also been made (Sundstrom, 1995; Forsten, 1995; Ohlemiller and Shields, 1995; ACT/DFA, 1995). These studies have shown different types of estimations and have highlighted some difficulties.

9.6.1.7 Other studies in the cone calorimeter using incident heat fluxes of 25 kW/m^2 (Hirschler and Smith, 1990) and 30 kW/m^2 (Ames et al., 1993) have also been made.

9.6.1.8* Input from the cone calorimeter (ASTM E 1474, *Standard Test Method for Determining the Heat Release Rate of Upholstered Furniture and Mattress Components or Composites Using a Bench Scale Oxygen Consumption Calorimeter*) and from the Lateral Ignition and Flame Spread Test (LIFT) apparatus (ASTM E 1321, *Standard Test Method for Determining Material Ignition and Flame Spread Properties*) can be used for predictions of furniture fire growth in a compartment.

9.6.1.9 Correlation between bench-scale and full-scale test results might be improved by incorporating factors that represent the effects of total mass, frame materials, frame style, and furniture design.

9.6.2 Bedding Materials.

9.6.2.1 Recent work has shown that estimates similar to those for upholstered furniture also apply to mattresses, relative to ASTM E 1474, *Standard Test Method for Determining the Heat Release Rate of Upholstered Furniture and Mattress Components or Composites Using a Bench Scale Oxygen Consumption Calorimeter*, and ASTM E 1590, *Standard Test Method for Fire Testing of Mattresses* (Babrauskas, 1993).

9.6.2.2 Experience has shown that bedding materials can substantially affect heat release from mattresses, particularly where the mattress itself has demonstrated fairly poor fire performance. Thus, in general, tests with mattresses and bedding are of interest mainly for systems with fairly high heat release rate values.

9.6.3 Wall Lining Materials.

9.6.3.1* Several fire models can predict heat release and fire growth of wall linings in a compartment.

9.6.3.2 A standard application procedure, found in ASTM E 1740, *Standard Test Method for Determining the Heat Release Rate and Other Fire-Test-Response Characteristics of Wall Covering or Ceiling Covering Composites Using a Cone Calorimeter*, has been developed for using the cone calorimeter with wall linings. For that standard, some of the issues regarding mounting techniques have been investigated (Fritz and Hunsberger, 1992).

9.6.3.3 It has been shown that the addition of up to two coats of paint on materials previously shown to have an acceptable fire performance as interior wall or ceiling finish materials is unlikely to change their fire performance to a significant extent (Waksman and Ferguson, 1974). The presence of multiple layers of paint on an interior surface (especially if one or more are partially peeling off) is a cause of potential added fire hazard, as the fire performance of the wall lining will be significantly worse than that associated with the material originally installed.

9.6.4* Floor Finish Materials. It has been shown that carpets can be tested in the cone calorimeter (ASTM E 1354, *Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*) at incident heat fluxes of 25 kW/m^2 to 30 kW/m^2 (Briggs et al., 1992; Ames et al., 1993; Hirschler, 1992a; Tomann, 1993). Lower heat fluxes might be more appropriate for testing floor finish products.

9.7 Bench-Scale Tests on Individual Materials.

9.7.1 Tests on individual materials offer important input information to fire safety analyses resulting from products burning in a room. This is especially important in terms of the emitted heat release rate. However, information on materials cannot address the issue of the potential interaction (synergistic or antagonistic) between the various materials contained in a product.

9.7.2 Results of fire tests on materials, therefore, are useful either as a predictor of the relative performance of the materials (based on the assumption that interactions between materials are negligible) or as input into specific fire models developed to predict the fire performance of products from that of the component materials.

9.7.3 Two methods have been proposed as empirical relative analyses of overall material fire performance. Both methods require testing of materials in the cone calorimeter (ASTM E 1354, *Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*).

9.7.3.1 The first method is an empirical relationship for predicting time to flashover from room wall lining materials in the same test as that covered by the Eurefic model specified in ISO 9705, *Fire Tests — Full Scale Room Tests for Surface Products* (options 100 kW and 300 kW; three walls and ceiling covered). This method has been applied successfully to the Eurefic test data. It uses input data from the cone calorimeter and the following equation:

$$t_{fo} = k_a + \frac{t_{ign}\sqrt{\rho}}{\sum \dot{Q}''_{Pk}} + k_b$$

where:

t_{fo} = predicted time to flashover in ISO 9705 (sec)
t_{ign} = time to ignition in the cone calorimeter at an incident flux of 25 kW/m^2 (sec)
ρ = the density (kg/m^3)
$\sum \dot{Q}''_{Pk}$ = total heat released per unit area during the peak period in the cone calorimeter at an incident heat flux of 50 kW/m^2
k_a = constant, 2.76×10^6 J $(kg/m)^{-0.5}$
k_b = constant, –46 sec

9.7.3.2 The other method is even simpler. It is a first-order approximation for relative time to flashover in a room-corner scenario, as shown in the following equation:

$$t_{fo} \alpha FPI = \frac{t_{ign}}{Pk\dot{Q}''}$$

where:

t_{ign} = time to ignition (seconds), measured in the cone calorimeter at an incident flux that is relevant to the scenario in question
FPI = fire performance index (sec m^2/kW)
$Pk\dot{Q}''$ = peak heat release rate per unit area at that same incident flux (kW/m^2)

9.7.3.3 If the material does not ignite, t_{ign} can be assigned a value of 10,000 seconds. The incident heating flux to be used should be relevant to the fire scenario being investigated and is to be specified by the investigator. This method is useful as a relative indication of propensity to flashover and cannot be used quantitatively (Hirschler, 1992a, 1992b, 1992c). However, it has been applied to two series of large-scale tests: FAA aircraft panels in a full-scale simulated aircraft interior (Lyon, 1994) and the Eurefic test data. Both test series were compared to cone calorimeter data at 540 kW/m^2. Figure 9.7.3.3 illustrates a comparison of full-scale times to flashover for FAA panels within an aircraft, and for wall lining materials in ISO 9705, *Fire Tests — Full Scale Room Tests for Surface Products,* with the ratio of time to ignition to peak rate of heat release in the cone calorimeter (ASTM E 1354, *Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*) at an incident flux of 50 kW/m^2.

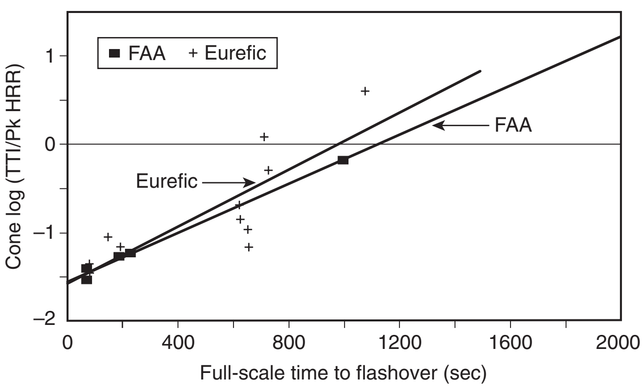


FIGURE 9.7.3.3 Comparison of Full-Scale Times to Flashover with the Ratio of Time to Ignition to Peak Rate of Heat Release in the Cone Calorimeter.

9.7.4 More recently, it has been found that correlation methods can be used to predict the results of room corner test methods (Dillon et al., 2001), principally whether flashover is likely to occur, or to predict whether a material is likely to result in a self-propagating fire (Karlsson 1994, Hirschler 1999). A useful survey was made by Janssens et al. (2003), of prediction methods, both correlations and via modeling.

9.8 Other Prediction Methods.

9.8.1* Several methods can be used as partial predictors of relative adequacy of performance of products and as additional tools.

9.8.2 Experienced observers are also capable of investigating which factors in the construction of upholstered furniture are most critical for potentially worsening fire performance to such an extent that a self-propagating fire can result.

Chapter 10 Ignition of Secondary Items by Radiative Heating

10.1 Methods/Tools. A set of analytical methods or tools is needed to provide a means for performing the evaluations embodied by the definitions in Section 8.3. In particular, methods are needed to predict the heating to ignition of materials contained within a fuel package as well as the radiative heat transfer to the material from other fuel packages or the hot gas layer. This chapter focuses on the radiative ignition of a material not in direct contact with a flame.

10.2* Radiative Ignition of Materials. Many different models of radiative ignition of materials exist, with varying levels of sophistication and usability. This section focuses on the method developed by Quintiere and Harkleroad (1985). As with many of the available models, this model assumes that surface temperature can be used as a criterion for piloted ignition. This directly implies that ignition cannot occur if the radiant heat flux, $\dot{q}''_e$, is less than a critical heat flux, $\dot{q}''_{o,ig}$. The ignition time, t_{ig}, varies with radiant flux above this critical flux. Based on a very simple heat transfer model, the time to ignition is determined by Equation 10.2, as follows:

$$t_{ig} = \left(\frac{\dot{q}''_{o,ig} / \dot{q}''_e}{b} \right)^2 \quad \textbf{(10.2)}$$

where:

t_{ig} = ignition time
$\dot{q}''_{o,ig}$ = critical heat flux
$\dot{q}''_e$ = incident radiative heat flux
b = a variable related to the thermal properties of the material

10.2.1 These data normally are obtained using the LIFT apparatus (ASTM E 1321, *Standard Test Method for Determining Material Ignition and Flame Spread Properties*) but also can be obtained using the cone calorimeter (ASTM E 1354, *Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*). Figure 10.2.1 illustrates the ignition behavior of one type of fiberboard using this method (Quintiere and Harkleroad, 1985). This method is valid for constant values of the incident heat flux, $\dot{q}''_e$. More general methods are also available in the referenced literature.

10.2.2 Equation 10.2 is based on a model of surface temperature (T_s) rise during heating given by Equation 10.2.2, as follows:

$$T_s = \left(\frac{\dot{q}''_e}{h} \right) F(t) \quad \textbf{(10.2.2)}$$

10.2.3 $F(t)$ in Equation 10.2.2 is determined from either of the following equations, where t_m is the time necessary for equilibration of the surface temperature:

$$F(t) = \frac{2ht^{1/2}}{(\pi k \rho c)^{1/2}} \text{ for } t < t_m$$

$$F(t) = 1 \text{ for } t \geq t_m$$

10.2.4 The first regime, for $t < t_m$, is modeled assuming no heat losses, while the second regime, for $t \geq t_m$, is modeled as a steady state. The ignition condition is derived by setting the surface temperature equal to the ignition temperature. The critical flux for ignition, $\dot{q}''_{o,ig}$, is defined by the flux necessary to reach the ignition temperature when $t \geq t_m$. Equation 10.2 is developed from the use of these considerations.

10.2.5 The product of the thermal conductivity, k, the density, ρ, and the heat capacity, c, is a fundamental material property often described simply as $k\rho c$. Because of the simplifying assumptions used, the value $k\rho c$ derived from LIFT (ASTM E 1321, *Standard*

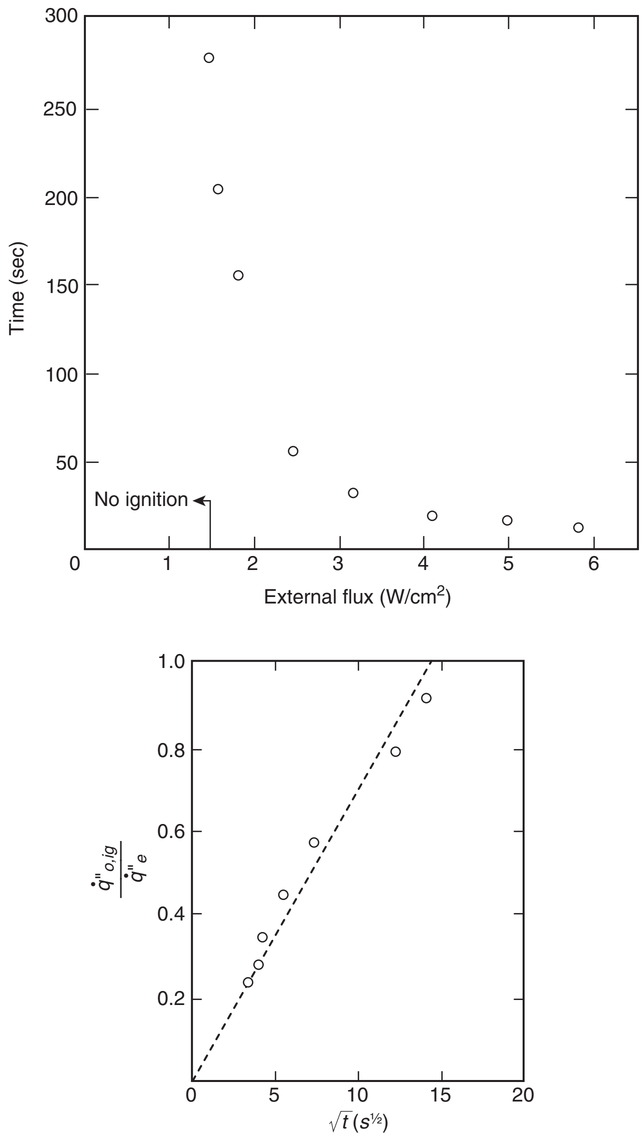


FIGURE 10.2.1 Ignition Behavior of a Particular Type of Fiberboard.

Test Method for Determining Material Ignition and Flame Spread Properties) or cone calorimeter (ASTM E 1354, *Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*) data is to be regarded as an effective $k\rho c$ and should not be expected to be equal to the $k\rho c$ derived from methods used to measure these heat transfer properties.

10.3 Radiative Heating.

10.3.1 In order to evaluate the ignition of a material contained in a target fuel package, the radiative heat flux to the material from other fuel packages and the hot layer must be determined. A number of methods can be used to make this determination. Additional information regarding methods used to evaluate the ignition of an item by radiative heating can be found in the *SFPE Engineering Guide to Piloted Ignition of Solid Materials Under Radiant Exposure.*

10.3.2 The radiative heat fluxes generated by a range of fuel packages over a range of distances from the fuel package have been investigated (Babrauskas, 1981–82). Based on knowledge of the burning rate of the radiating fuel package, the heat flux at specific distances from the fuel package can be estimated. Incident flux levels of 10 kW/m^2, 20 kW/m^2, and 40 kW/m^2 are defined as critical flux for ignition of general fuels and are described as easy, normal, and difficult to ignite, respectively. As noted in Section 10.2, the heat flux and duration of radiative exposure determine whether ignition can occur.

10.3.3 Equations 10.3.3a, 10.3.3b, and 10.3.3c are used to determine the critical rate of heat release necessary to enable a burning object to ignite a target object that is classified as easy, normal, or hard to ignite, respectively, at a distance, *D*:

$$\dot{Q} = 30\times10^{\left(\frac{D+0.08}{0.89}\right)} \quad \textbf{(10.3.3a)}$$

$$\dot{Q} = 30\times10^{\left(\frac{D+0.05}{0.019}\right)} \quad \textbf{(10.3.3b)}$$

$$\dot{Q} = 30\times10^{\left(\frac{D+0.02}{0.0092}\right)} \quad \textbf{(10.3.3c)}$$

where:
$\dot{Q}$ = heat release rate (kW)
D = distance (m)

10.3.3.1 If the rate of heat release of this burning object is increasing, the time at which the fire's rate of heat release is first reached is the time to ignition of the target object.

10.3.3.2 Equations 10.3.3a, 10.3.3b, and 10.3.3c are plotted in Figure 10.3.3.2. This graph can be used as a solution by reading up the appropriate curve to locate the separation distance, then finding the corresponding critical rate of heat release.

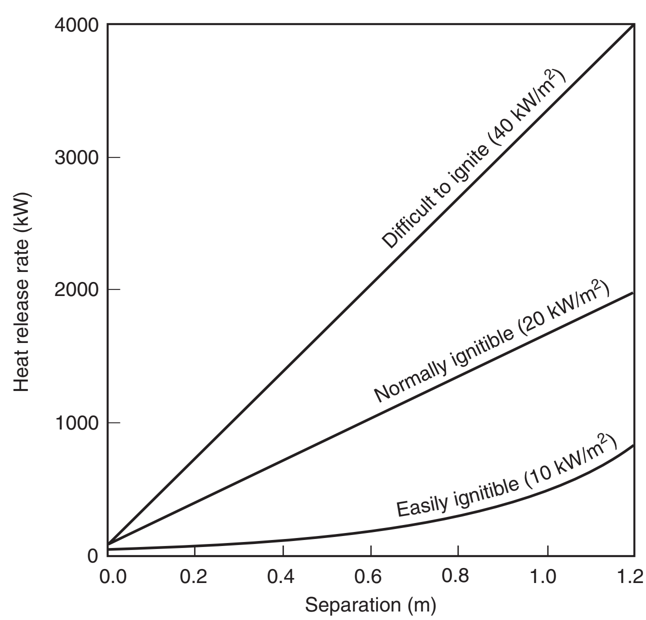


FIGURE 10.3.3.2 The Inverse Equation — Separation Distance Versus Rate of Heat Release.

10.3.3.3 Separation distance values of 140 cm, 90 cm, and 40 cm for easy-, normal-, and hard-to-ignite objects, respectively, represent distances beyond which the target objects are not considered part of the fuel package.

10.3.4 Two simple methods for evaluating radiation from pool fires to targets outside the flame have been developed (Mudan and Croce, 1988; Shokri and Beyler, 1989). Although these methods are based on pool fire test data, they can be applied to fuel packages. No studies have been performed to validate these methods where applied to furniture items. The pool fire data include diameters of 1 m to 50 m. Most fuel packages are at the low end of this range. The procedures for these methods are outlined in 10.3.4.1 and 10.3.4.2. Both methods model the flame as a cylindrical radiator with a specified emissive power. Configuration factors are then employed for the radiant heat flux calculation. The two methods differ only in their flame radiator height expressions and emissive power expressions. Additional information regarding radiation from pool fires can be found in the *SFPE Engineering Guide for Assessing Flame Radiation to External Targets from Pool Fires.*

10.3.4.1 The radiator is described as a cylinder with a radius determined by the size of the base of the fuel package. The height of the radiator is determined by a flame height correlation. Table 10.3.4.1 shows the flame height expressions used in the two models. The emissive powers used in the two models are given in Table 10.3.4.1 and are illustrated in Figure 10.3.4.1(a) and Figure 10.3.4.1(b). The radiant flux to the target from the fuel package, $\dot{q}''_{r,fp}$, is determined by the following equation:

$$\dot{q}''_{r,fp} = F_{fp-dt}E$$

where:

F_{fp-dt} = configuration factor between the cylindrical radiator (fuel package)

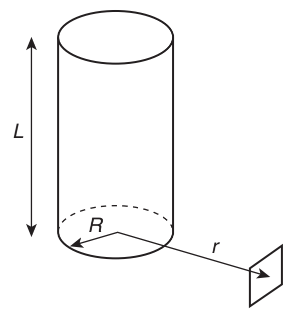
E = emissive power of the radiator

10.3.4.2 The configuration factors for several relevant geometries are shown in Figure 10.3.4.1(a) and Figure 10.3.4.1(b). These figures show the geometry, the equation, and a graph of the configuration factor. Configuration factors for other geometries related to those shown can be generated from the configuration factors provided, since configuration factors are cumulative. For instance, the worst-case configuration at a given distance from the radiator is a target facing the flame at half the radiator height.

10.3.4.3 This configuration factor can be created by considering the radiator to be composed of two cylinders, one above the target and one below. Because, in this case, the two cylinders are equal in size, the final configuration factor is simply twice the configuration factor for a radiator with a height equal to half the flame height.

10.3.5* The radiation from the hot gas layer can be estimated by methods similar to those described in 10.3.4 for the flame.

$$F_{d1\text{-}2,V} = \frac{1}{\pi S}\tan^{-1}\left(\frac{h}{\sqrt{S^2-1}}\right) - \frac{1}{\pi S}\tan^{-1}\sqrt{\frac{(S-1)}{(S+1)}} + \frac{Ah}{\pi S\sqrt{A^2-1}}\tan^{-1}\sqrt{\frac{(A+1)(S-1)}{(A-1)(S+1)}}$$



where:

$$S = \frac{r}{R}, \quad h = \frac{L}{R},$$

$$A = \frac{(h^2 + S^2 + 1)}{2S}$$

$$B = \frac{1 + S^2}{2S}$$

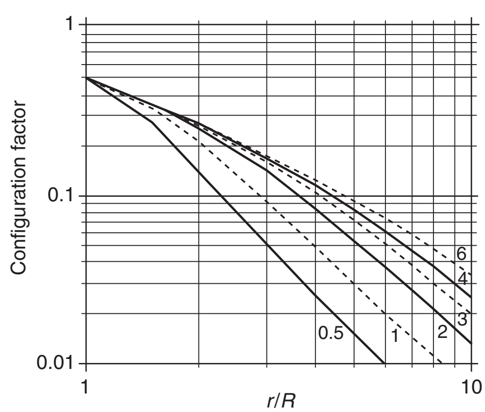


FIGURE 10.3.4.1(a) Configuration Factor for a Vertical Target and a Vertical Cylindrical Radiator.

Table 10.3.4.1 Flame Height and Emissive Power

Expression	Model 1*	Model 2†
Flame height	$H = 420\left(\frac{\dot{Q}}{\rho_a \Delta H_c \sqrt{gD}}\right)$	$H = 0.23\dot{Q}^{2/5} - 1.02D$ [m,kW]
Emissive power	$E = 140(e^{-0.12d}) + 20(1 - e^{-0.12d})$	$E = 58(10^{-0.00823d})$

H = flame height (m); $\dot{Q}$ = heat release rate (kW); ρ_a = density of air (kg/m^3); ΔH_c = heat of combustion (kJ/kg); g = gravitational constant (9.81 m/sec^2); D = the diameter of the fire (m); E = emissive power of the radiator (kW/m^2); d = distance between objects (m).

*Mudan and Croce, 1988.

†Shokri and Beyler, 1989.

The hot layer radiant can be modeled as a blackbody at the hot gas layer temperature, T_h. The configuration factor between the layer and the target, F_{hL-dt}, can be estimated based on the configuration factor between a flat rectangular radiator positioned at the location of the hot gas layer interface. The incident radiant heat flux from the layer to the target, $\dot{q}''_{r,h1}$, is determined by Equation 10.3.5:

$$\dot{q}''_{r,h1} = F_{hL-dt}\sigma T_h^4 \qquad \textbf{(10.3.5)}$$

where:

σ = Stefan–Boltzmann constant (5.67×10^{-11} kW/m^2 K^4)

F_{hL-dt} = configuration factor between the layer and the target

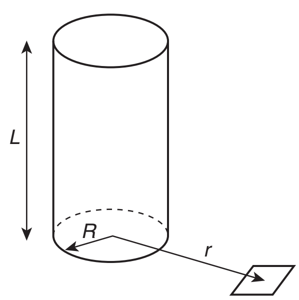
T_h = Hot gas layer temperature in Kelvin (°C + 273)

10.3.6 The worst case is a configuration factor of 1, which occurs if the target surface is facing the hot layer interface and is very close to the interface. The configuration factors for several relevant geometries are shown in Figure 10.3.6(a) and Figure 10.3.6(b). These figures show the geometry, the equation, and a graph of the configuration factor. Configuration factors for other geometries related to those shown can be generated from the configuration factors provided, since configuration factors are cumulative. For instance, if the target is at the center of the room and facing upward, the configuration factor is the sum of four configuration factors, one for each quadrant of the room. If the target is centered in the room, all four configuration factors are equal. If the target is close to the radiator, the maximum individual configuration factor is 0.25, and the maximum configuration factor is four times this value (i.e., 1.0, as previously discussed).

10.4 Example Methods. The methods described in Chapter 10 are examples of those that can be used for this type of analysis. They might not be the best methods for every situation. Nothing in this chapter should be taken to exclude the use of better methods than those discussed.

$$F_{d1\text{-}2,H} = \frac{(B - 1/s)}{\pi\sqrt{B^2 - 1}}\tan^{-1}\sqrt{\frac{(B+1)(S-1)}{(B-1)(S+1)}} - \frac{(A - 1/s)}{\pi\sqrt{A^2 - 1}}\tan^{-1}\sqrt{\frac{(A+1)(S-1)}{(A-1)(S+1)}}$$

where:



$$S = \frac{r}{R}, \quad h = \frac{L}{R},$$

$$A = \frac{(h^2 + S^2 + 1)}{2S}$$

$$B = \frac{1 + S^2}{2S}$$

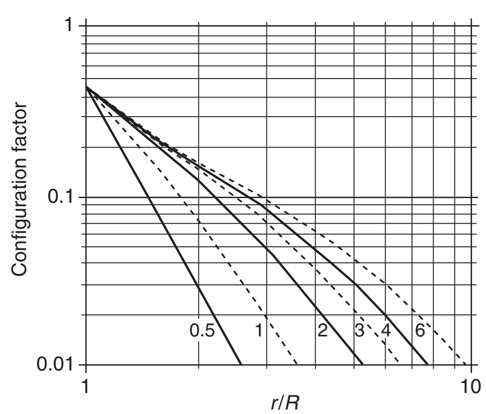
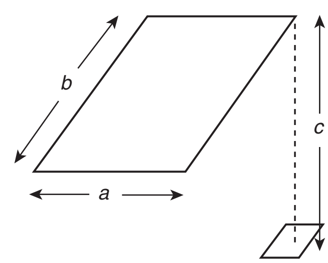


FIGURE 10.3.4.1(b) Configuration Factor for a Horizontal Target and a Vertical Cylindrical Radiator.

$$F_{d1\text{-}2} = \frac{1}{2\pi}\left[\frac{X}{\sqrt{1+X^2}}\tan^{-1}\left(\frac{Y}{\sqrt{1+X^2}}\right) + \frac{Y}{\sqrt{1+Y^2}}\tan^{-1}\left(\frac{X}{\sqrt{1+Y^2}}\right)\right]$$

where:
$X = a/c$
$Y = b/c$.



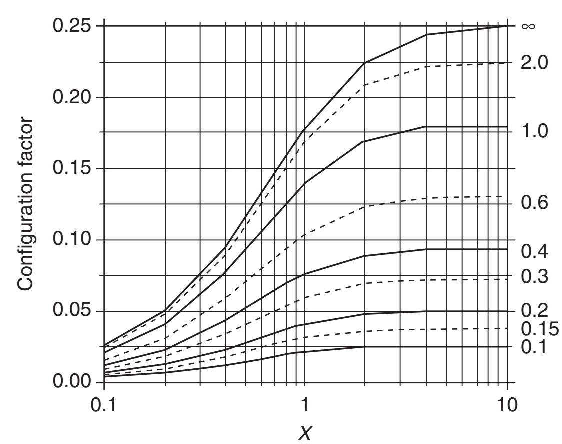
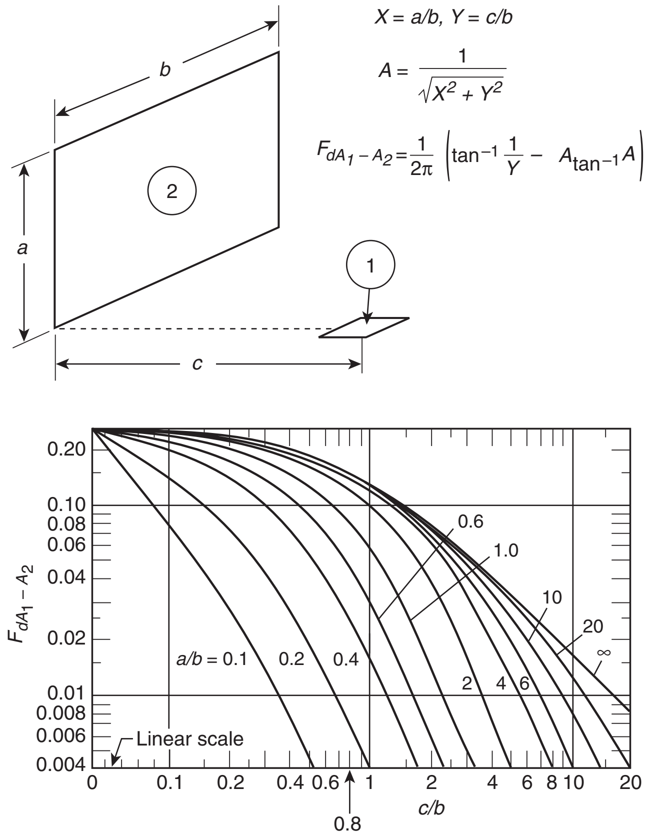


FIGURE 10.3.6(a) Configuration Factor for One Quadrant of the Hot Gas Layer to a Target Facing the Hot Layer.



$$A = \frac{1}{\sqrt{X^2 + Y^2}}$$

$$F_{dA_1-A_2} = \frac{1}{2\pi}\left(\tan^{-1}\frac{1}{Y} - A\tan^{-1}A\right)$$

FIGURE 10.3.6(b) Configuration Factor for One Quadrant of the Hot Gas Layer to a Target Not Facing the Hot Layer.

Annex A Explanatory Material

Annex A is not a part of the recommendations of this NFPA document but is included for informational purposes only. This annex contains explanatory material, numbered to correspond with the applicable text paragraphs.

A.3.3.2 Flashover. Flashover occurs when the surface temperatures of combustible contents rise, producing pyrolysis gases, and the room heat flux becomes sufficient to heat all such gases to their ignition temperatures. *(See Section 7.1.)*

A.3.3.3 Fuel Package. For a given group of items, there is no precise grouping that constitutes a fuel package. The purpose of the fuel package definition guidance provided in Chapter 8 is solely to facilitate the application of the methods described in Chapter 9 for estimating heat release rates.

A.3.3.4 Interior Finish. The term *interior finish* includes interior wall and ceiling finish and interior floor finish. With respect to interior wall and ceiling finish, this means the exposed interior surfaces of buildings including, but not limited to, fixed or movable walls and partitions, columns, and ceilings. With respect to interior floor finish, this means the exposed floor surfaces of buildings, including coverings that might be applied over a normal-finished floor or stairs, including risers. Furnishings, which in some cases are secured in place for functional reasons, should not be considered as interior finish.

A.3.3.5 Item. An item can be a collection of combustible materials such as chairs, wastebaskets with contents, or a combustible wall or floor. A precise definition of an item is not generally possible or necessary.

A.4.8 Examples of codes and standards that include performance-based design options include *NFPA 5000, Building Construction and Safety Code*, NFPA *101, Life Safety Code*, NFPA 1, *Fire Code*, NFPA 914, *Code for Fire Protection of Historic Structures*, NFPA 909, *Code for the Protection of Cultural Resource Properties — Museums, Libraries, and Places of Worship*, NFPA 301, *Code for Safety to Life from Fire on Merchant Vessels*, NFPA 92, *Standard for Smoke Control Systems*, NFPA 130, *Standard for Fixed Guideway Transit and Passenger Rail Systems*, and the *ICC Performance Code® for Buildings and Facilities*.

A.6.2.4 The computer-based models are addressed in the following publications:

(1) Bukowski et al. (1989a)
(2) Bukowski et al. (1989b)
(3) Cooper et al. (1990)
(4) Mitler and Rockett (1987)
(5) Nelson (1990)

A.7.1.2 Observations include the following:

(1) In a series of full-scale compartment burnout tests (surface area of 55 m^2), the average upper gas temperature rises ranged from 198°C to 959°C, with an average of 584°C for fully developed fires in an enclosure (Harmathy, 1972a, 1972b).
(2) In a study of the behavior of fully developed fires in single compartments by several laboratories, gas temperatures that were centrally measured at a point below the ceiling that was one-fourth the distance to the floor reached an average of 1070°C to 1145°C during three series of tests (Thomas and Heselden, 1972; Heselden, 1973).
(3) Flames exiting the doorway (a criterion for possible flashover) were observed during tests when the gas temperature measured approximately 10 mm below the ceiling reached 600°C (Hagglund et al., 1974). When this criterion was applied to a series of full-scale mattress fires, two out of ten exhibited potential to flashover (Babrauskas, 1977). These two mattress fires produced maximum gas temperatures of 938°C and 1055°C.
(4) In full-scale enclosure experiments, an average upper room temperature ranging from 450°C to 650°C provided sufficient radiation transfer to ignite crumpled newspaper at floor level in the compartment (Fang, 1975). The average upper room gas temperature needed for ignition of the newspaper was 540°C ± 40°C [Some temperatures were measured at the mid-height of the room (low values); temperatures measured 25 mm (1 in.) below the ceiling almost always exceeded 600°C].
(5) During tests in the living room of a mobile home, ignition of crumpled newspaper indicators was observed, with upper room temperatures ranging from 673°C to 771°C (Budnick, 1978; Klein, 1978; Budnick et al., 1978; Budnick and Klein, 1979). In those tests in which no full room involvement occurred, maximum upper room temperatures ranged from 311°C to 520°C. Tests reaching flashover and starting in the master bedroom of a typically constructed, single-width mobile home showed peak temperatures ranging from 634°C to 734°C at flashover. Temperatures were measured 25 mm (1 in.) below the ceiling in the center of the room.

(6) Full-scale and quarter-scale tests of submarine hull insulation found ignition of newspaper on the floor at room air and doorway air temperatures of at least 650°C and 550°C, respectively (Lee and Breese, 1979). For tests during which flashover was not obtained, the maximum temperatures achieved were 427°C and 324°C, respectively. The authors noted, however, that ignition of newsprint or a particular minimum doorway or interior air temperature is only a rough indicator of flashover because of the variation in the thermal and physical properties of crumpled newsprint, the nonuniform distribution of temperatures throughout the compartment, and the differences between tests of the combined thermal radiation from the smoke, the hot air, and the heated surfaces. The hot air inside the compartment usually became well mixed by the time it exited through the doorway. Thus, it was concluded that doorway temperatures might be more reliable flashover indicators than interior air temperatures.

(7) Maximum temperatures of over 800°C were observed during a flashover test of a urethane foam block chair (Babrauskas, 1979). For tests of upholstered chairs during which flashover did not occur, temperatures remained below 600°C.

(8) During a series of 16 full-scale fire tests of residential basement rooms, ignition of paper flashover indicators at floor level with an average upper room gas temperature of 706°C ± 92°C indicated a possibility of flashover of 90 percent (Fang and Breese, 1980).

(9) During a study of burning wood cribs and plastic cribs in a room, a gap was found between low-temperature fires (ceiling layer gas temperature <450°C) and high-temperature fires (ceiling layer gas temperature >600°C) (McCaffrey and Rockett, 1977; Quintiere and McCaffrey, 1980). The potential for flashover was identified by the fact that cellulose filter paper indicators ignited or were destroyed in the five cases (out of 16) involving high gas temperatures.

(10) Thomas's semi-empirical calculation of the rate of heat release necessary to cause flashover in a compartment (Thomas, 1981) is based on a simple model of flashover. It predicts a temperature rise of 520°C and a blackbody radiation level of 22 kW/m^2 to an ambient surface that is not in the proximity of burning wood fuel at the predicted critical heat release rate necessary to cause flashover.

A.7.1.3 Generalizations include the following:

(1) The concept of using the heat flux to exposed items within the fire room as a criterion for flashover was first suggested in 1974 (Parker and Lee, 1974). It was stated that, at a heat flux of 20 kW/m^2 at floor level, cellulosic fuels in the lower part of the room are likely to ignite.

(2) Table A.7.1.3 provides the critical ignition fluxes for some materials for a 60-second exposure (Babrauskas, 1977). The unpiloted values are probably more appropriate for determination of full room involvement, since the distance between the flames and the item to be ignited is considerable. A value of 20 kW/m^2 represents, according to W. K. Smith (date unknown), an unpiloted ignition time of approximately 180 seconds for box cardboard and is close to an ultimate asymptotic value.

(3) In one study of a series of room burns, strips of newsprint placed at floor level ignited at fluxes of 17 kW/m^2 to 25 kW/m^2, while 6.4 mm (¼ in.) thick fir plywood ignited at 21 kW/m^2 to 33 kW/m^2 (Fang, 1975).

(4) In mobile home tests in which flashover occurred, the minimum total incident heat flux at the center of the floor was 15 kW/m^2 (Budnick, 1978).

(5) In submarine compartments, average heat fluxes at floor level of 17 kW/m^2 to 30 kW/m^2 at flashover were found (Lee and Breese, 1979).

(6) In basement room tests, substantial agreement was found between the time to ignition of newsprint flashover indicators and the time at which the incident heat flux measured at the center of the floor in the burn room reached a level of 20 kW/m^2 (Fang and Breese, 1980).

(7) Ignition of filter paper flashover indicators in tests with wood and plastic cribs was observed at a minimum heat flux of 17.7 kW/m^2, applied for at least 200 seconds (Quintiere and McCaffrey, 1980). Under more controlled laboratory conditions, with radiant exposure to the same target configuration, the paper was charred black at 25 kW/m^2 and ripped at 120 seconds but only decomposed to a brown color under 15 kW/m^2. Thus, the criterion recommended was a heat flux of 20 kW/m^2.

Table A.7.1.3 Critical Ignition Heat Flux at a 60-Second Exposure

Material	Flux (kW/m^2) Piloted	Flux (kW/m^2) Unpiloted
Newspaper want ads	46	48
Box cardboard	33	43
Polyurethane foam	19	—

A.7.2.1 Two alternative approaches to that of Thomas (1981) have been proposed to estimate the onset of flashover within a room.

A.7.2.2 The first approach (Babrauskas, 1980; Babrauskas and Krasny, 1985) is based on a simple combustion model with a flashover criterion of $\Delta T = 575°C$. It provides a simple rule to estimate the minimum heat release rate to produce flashover, as determined in Equation A.7.2.2a:

$$\dot{Q} = 0.6 A_{vent} \sqrt{H_{vent}} \qquad \textbf{(A.7.2.2a)}$$

where:

$\dot{Q}$ = estimated rate of heat release (MW)
A_{vent} = door area (m^2)
H_{vent} = door height (m)

The $A_{vent}\sqrt{H_{vent}}$ product is usually designated as the "ventilation factor."

Equation A.7.2.2a results from assuming that the rate of heat release of the fire is proportional to the energy released per kilogram of air consumed (approximately 3.00 MJ/kg) and to the fraction of the maximum airflow into the compartment at the onset of flashover (an assigned value of 0.4).

Equation A.7.2.2a has been shown to generate adequate agreement with experimental data. In two-thirds of the cases studied, the rate of heat release of the fire ranged between the results of Equations A.7.2.2b and A.7.2.2c:

$$\dot{Q} = 0.45 A_{vent} \sqrt{H_{vent}} \quad \textbf{(A.7.2.2b)}$$

$$\dot{Q} = 1.05 A_{vent} \sqrt{H_{vent}} \quad \textbf{(A.7.2.2c)}$$

A.7.2.3 Another approach was based on a regression analysis in order to provide a correlation to predict upper-layer gas temperature (McCaffrey et al., 1981; Quintiere, 1982). Using data from more than 100 experiments, the correlation found needed two dimensionless quantities, as shown in Equation A.7.2.3a:

$$\Delta T = 480 \left(\frac{\dot{Q}}{\sqrt{g} C_p \rho_0 T_0 A \sqrt{H}} \right)^{2/3} \left(\frac{h_k A_w}{\sqrt{g} C_p \rho_0 A \sqrt{H}} \right)^{-1/3} \quad \textbf{(A.7.2.3a)}$$

where:

ΔT = temperature rise relative to ambient (°C)
h_k = effective heat transfer coefficient to ceilings/walls
A_w = effective surface area for heat transfer, including door area
g = gravitational constant
C_p = specific heat of gas
ρ_0 = ambient gas density
T_0 = initial ambient absolute temperature

A method for calculating the effective heat transfer coefficient, h_k, ranges has also been published (Pape and Waterman, 1976).

The correlation coefficient between the experimental data and the predictions of Equation A.7.2.3a ranges between 0.959 and 0.947, depending on whether the floor is included in the calculation of the wall area and the effective heat transfer coefficient.

By substituting typical values for C_p, ρ_0, T_0, and a flashover criterion of ΔT = 500°C, Equation A.7.2.3a can be reduced to Equation A.7.2.3b as follows:

$$\dot{Q} = 0.61 \left[h_k A_w A (h)^{1/2} \right]^{1/2} \quad \textbf{(A.7.2.3b)}$$

where $\dot{Q}$ is in MW, A_w and A are in m^2, h is in m, and h_k is in kW/(m^2 K^{-1}).

A.9.1 With regards to NFPA 556, *Guide on Methods for Evaluating Fire Hazard to Occupants of Passenger Road Vehicles*, it should be noted that the passenger road vehicle can serve as a fuel source in a structure in which the passenger road vehicle is located.

A.9.4.1.2 A guide on fire hazard assessment of rail transportation vehicles, ASTM E 2061, *Guide for Fire Hazard Assessment of Rail Transportation Vehicles*, gives clear guidelines on how to address this issue. It states that, in fire scenarios intended to reflect vandalism of the initially fabricated seat (or mattress) assembly, before fire ignition, an example of vandalism may be a knife cut 6 in. long and 1 in. deep in the middle of an actual seat (or mattress) assembly, thus suggesting that this is one way of testing an upholstered system. It goes on to state that any bench-scale representations of the proposed vandalism should take into account test method sample sizes. A standardized bench-scale test method exists (albeit only for a specific occupancy: correctional facilities) to assess the heat release and ignitibility of composites of mattresses or furniture in a vandalized manner, to expose the filling material. ASTM F 1550, *Standard Test Method for Determination of Fire-Test-Response Characteristics of Components or Composites of Mattresses or Furniture for Use in Correctional Facilities After Exposure to Vandalism, by Employing a Bench Scale Oxygen Consumption Calorimeter*, can be used to assess, for correctional facilities, upholstery composites that have been vandalized in a prescribed manner to expose the filling material, by using the cone calorimeter (ASTM E 1354, *Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*).

A.9.4.1.3 The ASTM Committee on Fire Standards assessed the precision of ASTM E 1537, *Standard Test Method for Fire Testing of Real Scale Upholstered Furniture*, ASTM E 1590, *Standard Test Method for Fire Testing of Mattresses*, and ASTM E 1822, *Standard Test Method for Fire Testing of Stacked Chairs*. Results of round-robin testing indicate significant variability in the test data. The results from full-scale fire tests such as those referenced above might be dependent upon the lab conducting the test, the test method itself, and the variability of the test specimen.

A.9.4.1.5 Several preliminary fire research projects have investigated the role of materials and product design characteristics on the flammability properties of room contents and furnishings (Babrauskas, 1981–82; Babrauskas et al., 1982; Babrauskas and Walton, 1986; Damant et al., 1989; Smiecinski et al., 1989; Schuhmann and Hartzell, 1989; Hirschler and Smith, 1990; Parker et al., 1990; Damant and Nurbakhsh, 1991; Hirschler and Shakir, 1991; Villa and Babrauskas, 1991; Gallagher, 1992; Barile, 1993; Grand et al., 1994).

A.9.4.2 NFPA *101*, *Life Safety Code*, as well as other U.S. building and fire codes, includes some requirements on the use of NFPA 286, *Standard Methods of Fire Tests for Evaluating Contribution of Wall and Ceiling Interior Finish to Room Fire Growth*, and of NFPA 265, *Standard Methods of Fire Tests for Evaluating Room Fire Growth Contribution of Textile or Expanded Vinyl Wall Coverings on Full Height Panels and Walls*, while international specifications often reference ISO 9705, *Fire Tests — Full Scale Room Fire Tests for Surface Products* (ASTM E 2257, *Standard Test Method for Room Test of Wall and Ceiling Materials and Assemblies*, has been developed as an alternative, technically equivalent version). Comparative details of the tests have been discussed (Hirschler, 1994). The fire performance of wall or ceiling finish is often assessed in American codes according to test results in the Steiner tunnel test (ASTM E 84, *Standard Test Method for Surface Burning Characteristics of Building Materials*; this test method is similar and technically equivalent). However, the results obtained from the Steiner tunnel test are not suitable for use in the calculations cited in this document (Belles et al., 1988).

A.9.4.4 An analysis of fire data and fire statistics from mattress and bedding products was conducted by the National Institute of Standards and Technology (NIST) and is reported in NIST Technical Note 1446, *Estimating Reduced Fire Risk Resulting from an Improved Mattress Flammability Standard* (Gann and Ohlemiller, 2002). The fire testing of mattresses for this study was conducted using a fire test method that involves testing a mattress with a set of burners, as described below. Overall, the study suggests that the use of bed systems with improved fire performance would achieve very significant reductions in fire risk. The fire performance of the best bed system tested in this study (about 400 kW) was predicted to lead to a much lower probability of flashover, leading to a one-third reduction in fire fatalities associated with bedroom fires. Technical work was based on earlier work by Ohlemiller et al. (NISTIR 6497, 2000).

The ignition source for the test conducted for NISTIR 6497 consists of two T-shaped burners. One burner impinged flames on the top surface of the mattress (at 12.9 L/min of propane, for 70 seconds), and the second burner impinged flames on the side of the mattress and on the side of the foundation (at 6.61 L/min for 70 seconds). Each burner incorporated a stand-off foot to set its distance from the test specimen surface. Both burners were mounted with a mechanical pivot point, but the side burner was locked in place to prevent movement about this pivot in normal usage. The top burner, however, was free to rotate about its pivot during a burner exposure and was lightly weighted so as to exert a downward force on the mattress top through its stand-off foot. Thus the burner would follow a receding top surface on the test specimen.

A.9.4.6.5.2 Some codes address testing of decorative objects constructed of foamed plastic and such as stage settings, foamed panels, and portable exhibit booths, by means of UL 1975, *Standard for Fire Tests for Foamed Plastics Used for Decorative Purposes,* which is similar to using a product calorimeter with an ignition source of 20 kW. UL 1975 uses a 340 g wood crib as the ignition source. More recently, those codes have added the option of using NFPA 289, *Standard Method of Fire Test for Individual Fuel Packages*, with the gas burner at the incident gas level of 20 kW as an alternative approach.

A.9.6.1.8 The Dayton University Furniture Fire Model uses input data from the cone calorimeter (ASTM E 1474, *Standard Test Method for Determining the Heat Release Rate of Upholstered Furniture and Mattress Components or Composites Using a Bench Scale Oxygen Consumption Calorimeter*) and the LIFT apparatus (ASTM E 1321, *Standard Test Method for Determining Material Ignition and Flame Spread Properties*) to predict the furniture fire growth and burnout in a room and the spread of combustion products (gases, smoke, heat) to other rooms (Dietenberger, 1992). It is a zone model, associated with the FAST room fire model developed by the National Institute of Standards and Technology (Jones and Peacock, 1989), and has significant flexibility. It can simulate a piece of furniture with up to four cushions. However, this fire model is of high complexity and uses a complex set of data inputs. The LIFT apparatus is used in the Dayton University model to derive three parameters associated with flame spread:

(1) The thermal inertia [$k\rho c$ in units of $(kW/m^2\ K)^2$ sec]
(2) The ignition temperature T_{ig} in°C
(3) The flame heating parameter (Φ, in units of kW^2/m^3)

It has been shown (Janssens, 1992) that information on concurrent flow flame spread (i.e., where the flame moves in the same direction as the prevalent wind) can be obtained directly from cone calorimeter data. On the other hand, opposed flow flame spread probably still needs LIFT data, especially to determine the flame heating parameter. The flame spread rate, V_p, is calculated using the following equation (where T_s is the initial surface temperature in °C):

$$V_p = \frac{\Phi}{k\rho c\left(T_{ig} - T_s\right)^2}$$

A.9.6.3.1 See Annex B for descriptions of fire models used to predict heat release and fire growth in compartments.

A.9.6.4 Fire performance of floor finish items is often assessed by determining the critical radiant flux in the flooring radiant panel (NFPA 253, *Standard Method of Test for Critical Radiant Flux of Floor Covering Systems Using a Radiant Heat Energy Source*, or ASTM E 648, *Standard Test Method for Critical Radiant Flux of Floor-Covering Systems Using a Radiant Heat Energy Source*; these test methods are similar and technically equivalent). However, the results of this test are not suitable for use in the calculations cited in this document (Briggs et al., 1992; Lawson, 1993; Tomann, 1993).

A.9.8.1 A "backyard test" can be a useful screening method for predicting the heat release rate of upholstered furniture. In this test, an actual piece of furniture (or a full-scale mockup) is exposed to the same ignition source as that in ASTM E 1537, *Standard Test Method for Fire Testing of Real Scale Upholstered Furniture*, in a relatively draft-free environment. Visual observations of the results are made, but no heat release measurements are made. This setup allows reasonable predictions of some heat release rate results in the actual instrumented fire tests. It does not provide any estimation of total heat release. Figure A.9.8.1(a) represents results where chairs were divided into those that produce peak rates of heat release of under 40 kW and those that produce rates over 300 kW. Of fourteen systems tested and deemed to give off low heat release rates, none actually exceeded peak values of 250 kW, and four exceeded 80 kW. Of six systems tested and deemed to give off high heat release rates, none gave off peak values lower than 80 kW, and three gave off values between 100 kW and 250 kW.

The actual experiments for which results are represented in Figure A.9.8.1(a) were all carried out with balanced, woven fabrics of different types but with the same foam and interliner barrier. A number of other individual experiments were made with other materials, and the reliability of the results was much less satisfactory. However, this work indicates the clear value of visual observation by those who are experienced.

An attempt also has been made to predict peak heat release rate values based on fabric weight. It has been shown that fabric weight alone might not be a reliable indicator of furniture heat release rate. In this case, a number of tests were carried out using a single specific fabric/interliner/foam/chair construction system. The only variable was the weight of the fabric. In a follow-up series of tests, a different type of fabric was used. All the results are shown in Figure A.9.8.1(b), which indicates that a fivefold increase in fabric weight was not

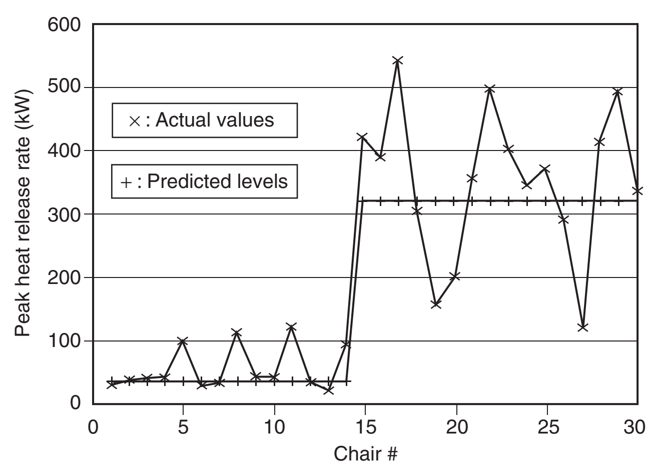


FIGURE A.9.8.1(a) Predictions of the Results of Full-Scale ASTM E 1537 Tests with Upholstered Furniture Items (Backyard Test) and Actual Observed Values.

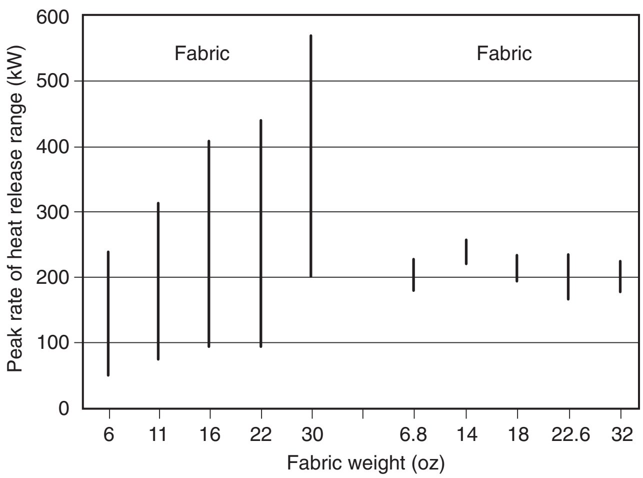


FIGURE A.9.8.1(b) Effect of Fabric Weight on Heat Release Rate in Full-Scale ASTM E 1537 Upholstered Furniture Tests Using Two Fabrics, A and B.

sufficient, in this particular case, to differentiate significantly among the fire performance of the chairs. In one series, a definite trend toward increased heat release with increased fabric weight was evident, even though the error bars overlapped. In the other case, all systems produced nondifferentiable results. This is somewhat surprising, since other work has shown that, in some systems, the effect of the fabric is the dominant one on fire performance (Hirschler and Shakir, 1991).

A.10.2 Table A.10.2(a) shows values of the critical heat flux, *b*, which is related to the thermal properties of the material, and t_m, the time required for equilibration of the surface temperature, for a wide range of materials. Table A.10.2(b) illustrates that ignition properties within a generic category of materials can vary substantially. The values provided in the tables are intended as hypothetical results only. They provide a general indication of the magnitudes and ranges of the parameters. The materials tested were not sufficiently characterized to allow specific use of the data in particular applications.

Table A.10.2(a) Ignition Properties of Materials

Material	$\dot{q}''_{o,ig}$ (W/cm^2)	b ($sec^{-0.5}$)	t_m (sec)
Plywood, plain, 0.635 cm	1.6	0.07	190
Plywood, plain, 1.27 cm	1.6	0.07	225
Plywood, FR, 1.27 cm	4.4	0.1	110
Hardboard, 6.35 mm	1	0.03	1190
Hardboard, 3.175 mm	1.4	0.05	420
Hardboard, gloss paint, 3.4 mm	1.7	0.05	468
Hardboard, nitrocellulose paint	1.7	0.06	306
Particle board, 1.27 cm stock	1.8	0.05	342
Douglas fir particle board, 1.27 cm	1.6	0.05	395
Fiber insulation board	1.4	0.07	205
Polyisocyanurate, 5.08 cm	2.1	0.36	8
Polystyrene, 5.08 cm	4.6	0.14	53
Polycarbonate, 1.52 mm	3	0.06	260
Foam, rigid, 2.54 cm	2	0.32	100
Foam, flexible, 2.54 cm	1.6	0.09	132
PMMA Type G, 1.27 cm	1.5	0.05	456
PMMA polycast, 1.59 cm	0.9	0.04	462
Carpet #1 (wool stock)	2.3	0.18	32
Carpet #2 (wool, untreated)	2	0.11	83
Carpet #2 (wool, treated)	2.2	0.12	72
Carpet (nylon/wool blend)	1.8	0.06	248
Carpet (acrylic)	1	0.06	250
Gypsum board, common, 1.27 cm	3.5	0.11	87
Gypsum board, FR, 1.27 cm	2.8	0.1	95
Gypsum board, wallpaper (S142M)	1.8	0.07	208
Asphalt shingle	1.5	0.06	306
Fiberglass shingle	2.1	0.08	161
GRP, 2.24 mm	1.6	0.09	132
GRP, 1.14 mm	1.7	0.06	279
Aircraft panel epoxy fiberite	2.8	0.13	57

Source: Quintiere and Harkleroad (1985).

Table A.10.2(b) Ignition Times of Different Materials in Cone Calorimeter

Material	Thickness (cm)	Time to Ignition (sec)	Flux (kW/m^2)
Flexible polyether-type polyurethane foam			
1.2 PCF conventional foam	5.1	11	20
1.5 PCF conventional foam	5.1	22	20
1.8 PCF conventional foam	5.1	28	20
1.2 PCF 117 foam	5.1	38	20
1.5 PCF 117 foam	5.1	39	20
1.8 PCF 117 foam	5.1	37	20
3.0 PCF melamine foam	5.1	77	20
Rigid polyether-type polyurethane foam			
1.2 PCF MDI-based foam	5.1	40	20
1.5 PCF MDI-based foam	5.1	55	20
2.0 PCF MDI-based foam	5.1	95	20
Plywood			
AB Douglas fir	1.27	330	35
AB Douglas fir	1.91	410	35
BC Douglas fir	1.27	160	35
BC Douglas fir	1.91	180	35
Birch ICG	1.27	490	35
Birch ICG	1.91	550	35
BC yellow pine	1.27	90	35
BC yellow pine	1.91	100	35
BC yellow pine	1.27	125	35
BC yellow pine	1.27	140	35

Note: All results are the mean of six replications.

A.10.3.5 Equation 10.3.5 assumes that the upper layer can be taken as a blackbody radiator. The emissivity is a function of the concentration of soot and gaseous combustion products, such as carbon monoxide, carbon dioxide, and water. It is assumed that, when the temperature of the upper layer is high enough to contribute significant radiative heat, the concentration of soot and gaseous combustion products is high enough for the upper layer to be optically thick, and an emissivity value of 1 is appropriate. This estimate is conservative with regard to upper-layer contribution to ignition. This estimate can be reduced on the basis of a detailed radiation analysis.

Annex B Room Fire Models to Predict Heat Release and Fire Growth

This annex is not a part of the recommendations of this NFPA document but is included for informational purposes only.

B.1 Limitations of Room Fire Models. Babrauskas stated in 1996 that the main limitation of room fire models is that they are not capable of predicting heat release rate and fire growth and that they can only predict the consequences of a user-specified fire (Babrauskas, 1996). This is particularly true when flame spread over large wall and ceiling surfaces is involved. For the most part, Babrauskas' statement is still valid today, although computational fluid dynamics (CFD) codes have the potential of addressing this limitation in the near future. However, there is one important exception. A great deal of work has been done on modeling of fire growth in a room/corner test. This work is reviewed in this annex.

B.2 The Room/Corner Test. There are several room/corner test standards (e.g., ASTM E 2257, *Standard Test Method for Room Fire Test of Wall and Ceiling Materials and Assemblies*; ISO 9705, *Fire Tests — Full Scale Room Tests for Surface Products*; NFPA 265, *Standard Methods of Fire Tests for Evaluating Room Fire Growth Contribution of Textile or Expanded Vinyl Wall Coverings on Full Height Panels and Walls*; and NFPA 286, *Standard Methods of Fire Tests for Evaluating Contribution of Wall and Ceiling Interior Finish to Room Fire Growth*) that are all based on the same concept. The test apparatus consist of a room is approximately 2.4 m (8 ft) wide by 3.6 m (12 ft) deep by 2.4 m (8 ft) high and has an open door in the front wall measuring approximately 0.8 m (32 in.) by 2.0 m (80 in.). The product to be tested is attached to the side walls, the back wall, and/or the ceiling depending on the standard test protocol that is followed. The product is exposed to the flame of a gas burner located in one of the rear corners of the room. The geometry of and heat output from the burner vary according to the test standard that is used. All products of combustion generated in the test are collected in a hood outside the room and extracted through an exhaust duct. Measurements typically include upper layer temperatures in the room, heat flux to the floor, and heat release and smoke production rate in the exhaust duct.

B.3 Models of the Room/Corner Test. There are three distinct types of room/corner test models: regression models, physics-based models, and analytical models. Regression models express a relationship between a particular room/corner test performance characteristic, usually the time to flashover, and small-scale fire test data for the same product. Regression models are based on a statistical analysis of room/corner and small-scale test data for a set of products and can be used as a screening tool. Physics-based models predict how the room environment varies as a function of time and how flames spread over the walls and ceiling of the compartment. There is a strong interaction between the two because the conditions in the room determine the heat that is transferred back to the wall and ceiling surfaces, which affects the flame spread and the heat release and smoke production rate of burning wall and ceiling sections. Analytical models predict fire growth, but do not simulate the room environment.

B.4 Regression Models.

B.4.1 Östman's Flashover Time Correlation. Östman and Nussbaum developed a correlation to predict time to flashover in the ISO 9705 room on the basis of ignition time (at 25 kW/m^2) and average heat release rate measured during the "peak burning period" (at 50 kW/m^2) in the cone calorimeter (ASTM E 1354, *Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*, and ISO 5660-1, *Reaction-to-fire tests — Heat release, smoke production and mass loss rate — Part 1: Heat release rate (cone calorimeter method)*, and the density of the product (Östman and Nussbaum, 1989). The original regression model was based on test data for 13 products. The correlation was revised in 1994 and 2002 based on expanded data sets for 28 and 57 products, respectively (Hansen and Hovde, 2002; Östman and Tsantaridis, 1994). The most recent study also involved application of the analytical model developed by Wickström and Göransson (1992) and a multivariate statistical method (multiple discriminant function analysis).

B.4.2 Cleary's Flashover Parameter. Cleary and Quintiere developed a parameter that provides an indication whether flashover is likely to occur in the ISO 9705 room/corner test (Cleary and Quintiere, 1991). The parameter is a function of the average heat release rate at peak burning, the ignition time, and the burning time measured in the cone calorimeter. Dillon et al., modified the parameter to account for the dynamics of the heat release rate curve and to predict the likelihood of flashover in NFPA 265, *Standard Methods of Fire Tests for Evaluating Room Fire Growth Contribution of Textile or Expanded Vinyl Wall Coverings on Full Height Panels and Walls*, and NFPA 286, *Standard Methods of Fire Tests for Evaluating Contribution of Wall and Ceiling Interior Finish to Room Fire Growth*, room/corner tests (Hansen and Hovde, 2001). They also presented correlations based on cone calorimeter data to predict the peak heat release rate and total smoke produced in a room/corner test that does not flash over.

B.4.3 Östman's Smoke Production Correlation. Östman and Tsantaridis found that total smoke production and peak smoke production rate prior to flashover can be predicted reasonably well from the total smoke production during the "peak burning period" and peak smoke production rate, respectively, measured in the cone calorimeter at a heat flux of 50 kW/m^2 (Östman and Tsantaridis, 1991). A more extensive analysis based on data for 28 products was published two years later (Östman and Tsantaridis, 1993). The products were divided into two groups: products with a flashover time of 10 minutes or greater and those with a flashover time of less than 10 minutes. For the first group, both average rate of smoke production and total smoke production in the cone calorimeter at 50 kW/m^2 appear to be a good indicator of smoke release in the room/corner test. For the second group of products, however, no good correlation could be found.

B.4.4 Karlsson's Flashover Time Correlation. Karlsson developed physics-based and analytical models of the ISO 9705 room/corner test (Karlsson, 1992). He used the physics-based model (see B.5.3 for a brief description) to generate a dataset of flashover times for virtual room/corner tests on a range of products with varying ignition, heat release rate, and flame spread characteristics. These characteristics can be measured in the cone calorimeter and the LIFT (Lateral Ignition and Flame Spread Test) apparatus (ASTM E 1321, *Standard Test Method for Determining Material Ignition and Flame Spread Properties*). The virtual dataset was then used to develop power law correlations to predict the time to flashover as a function of the small-scale data for two specimen configurations: test specimens on walls and ceiling (scenario A) and test specimens on walls only (scenario B). Since opposed-flow flame spread does not significantly affect fire growth in scenario A, the opposed-flow flame spread properties from the LIFT apparatus could be omitted in the power law correlation for this scenario without loss of accuracy.

B.4.5 Kokkala's Heat Release and Ignitibility Indices. Kokkala, Thomas, and Karlsson derived two indices, an ignitibility index and a heat release index, that were combined into a fire growth parameter to predict the time to flashover in the ISO 9705 room/corner test (Kokkala et al., 1993). Both indices are calculated from test results obtained in the cone calorimeter at a heat flux of 50 kW/m^2. The ignitibility index is the inverse of the time to ignition. The heat release rate index is obtained by integrating the rate of heat release in time, weighted so that the initial heat release rates are of higher importance than those at later times. The Building Code of Australia now permits the use of Kokkala's indices to demonstrate that an interior finish material meets specific ISO 9705 performance requirements.

B.4.6 Heskestad's Smoke Production Correlation. Heskestad and Hovde developed a regression model to predict the smoke production rate in the ISO 9705 room/corner test at the time when the heat release rate is 400 kW (Heskestad and Hovde, 1999). This model is valid for products with a time to flashover of less than 10 minutes. The independent variables are ignition time, time to peak heat release rate, total heat released, and total carbon monoxide production in the cone calorimeter at a heat flux of 50 kW/m^2.

B.4.7 Dietenberger's Smoke Production Correlation. Dietenberger found a direct proportionality between the average specific extinction area (SEA) in the ISO 9705 room/corner test and the peak SEA measured in the cone calorimeter at a heat flux of 35 kW/m^2 (Dietenberger and Grexa, 2000). The mass loss rate in the room/corner test was estimated as the ratio of the heat release rate measured in the room/corner test to the effective heat of combustion measured in the cone calorimeter. The ISO 9705 room/corner tests considered for this study were conducted with test specimens on the walls only.

B.4.8 IMO Criteria for Fire-Restricting Materials. The *High Speed Craft (HSC) Code* of the International Maritime Organization (IMO) allows for the use of combustible compartment linings and furniture, provided they consist of "fire-restricting materials." The criteria for linings are based on performance in the ISO 9705 room/corner tests and consist primarily of limits for the heat release and smoke production rates and total values. Furniture components must meet specific criteria based on results obtained from cone calorimeter testing at a heat flux of 50 kW/m^2. The cone calorimeter criteria are consistent with the ISO 9705 room/corner test criteria and were established on the basis of a research program conducted by the United States Coast Guard at Southwest Research Institute in San Antonio, Texas (Grenier et al., 2000).

B.4.9 Hansen's Smoke Production Model. A model to predict smoke production in the ISO 9705 room/corner test on the basis of cone calorimeter measurements obtained at a heat flux of 50 kW/m^2 was developed from multiple discriminant analysis of a dataset for 28 products (Hansen and Hovde, 2001).

B.5 Physics-Based Models.

B.5.1 Steckler's Model. Steckler, at the National Bureau of Standards, developed flame spread algorithms and combined them with a two-zone compartment fire model (Steckler, 1983). The model was based on a conceptual framework developed by Quintiere (Quintiere, 1981). Steckler's algorithms do not address upward and wind-aided flame spread, and only calculate lateral spread in the direction away from the corner.

B.5.2 OSU Model. The Ohio State University (OSU) model, developed by Ed Smith and several of his graduate students at OSU, was one of the first comprehensive fire models of a room/corner fire. The model predicts fire growth of wall and ceiling linings on the basis of ignition, flame spread, and heat and smoke release data obtained from the OSU small-scale heat release calorimeter (ASTM E 906/E 906M, *Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products*). The physical basis of the OSU model is discussed in detail in a paper by Janssens, who provided a critical analysis of the model and questioned its validity (Janssens, 1994). The OSU model has been shown to provide predictions that are in reasonable agreement with experimental data for room/corner tests on wood products but is less satisfactory for other configurations (wall fires) and other types of products (Tran, 1994).

B.5.3 Karlsson's Physics-Based Model. Karlsson's Ph.D. dissertation describes a two-zone model of the room/corner test (Karlsson, 1992). The layer interface is fixed at the soffit height, and the upper layer temperature is estimated on the basis of a modified version of a steady-state correlation (McCaffrey et al., 1981). Fire growth algorithms consist of equations for upward and downward flame spread. The former require ignition and heat release properties of the product that is tested. The latter use lateral flame spread data from the LIFT apparatus. The model considers the following five sources of heat release:

(1) The gas burner
(2) The vertical wall area behind the burner flame
(3) A horizontal strip of material at the wall-ceiling intersection corresponding to the thickness of the ceiling jet
(4) The wall material in the upper layer after flame spread has started
(5) The wall linings burning below the hot gas layer

B.5.4 Quintiere's Model. This model is similar to Karlsson's model (see B.5.3), except that the room gas temperature is assumed to be uniform throughout the compartment (one zone) and wind-aided flame spread is calculated on the basis of the solution of an ordinary differential equation as opposed to an analytical solution (Quintiere, 1993). In addition, Quintiere's model also accounts for burnout.

B.5.5 Janssens' Model. This model is a modified version of Quintiere's model (Janssens et al., 1995). The model includes algorithms to characterize the geometry and wall heat flux of the burner flame (Janssens et al., 1995). Janssens also developed improved procedures to obtain ignition, flame spread, and heat release properties from cone calorimeter and LIFT test data (Janssens, 1991).

B.5.6 Opstad's Model. Opstad used the KAMELEON CFD code developed at SINTEF in Norway to simulate the ISO 9705 room test (Opstad, 1995). An engineering approach was used to model flame spread over surfaces on the basis of material properties derived from cone calorimeter data (Opstad and Hovde, 1994).

B.5.7 Wade's Model. This model is described in detail in Colleen Wade's M.S. thesis (Wade, 1996). Quintiere's flame spread algorithms were coupled with a two-zone enclosure fire model. Wade uses Janssens' procedures to obtain ignition and flame spread data, and improved Quintiere's method to obtain heat release rates under time-varying heat flux conditions from cone calorimeter data. A significantly revised version of the model was published in 2004 (Wade, 2004).

B.5.8 Yan's Model. Yan combined a CFD code developed at Lund University in Sweden with a more fundamental pyrolysis model (Yan and Holmstedt, 1996). This approach is not as versatile as Opstad's model, because the pyrolysis model can only be used for certain types of charring fuels, and it requires an extensive number of fundamental thermo-physical properties of the material.

B.5.9 HAI Model. The flat wall flame spread model developed at Hughes Associates (HAI) for the U.S. Navy (Beyler et al., 1997) was improved to include opposed-flow flame spread and hot layer effects (Lattimer et al., 2003). The latter is accomplished by coupling the flame spread algorithms with the two-zone compartment fire model CFAST. The resulting fire growth model has been validated against ISO 9705 test data.

B.5.10 SwRI Model. Janssens' model was further modified by Southwest Research Institute (SwRI) to improve heat rate predictions and to include smoke production rate calculations (Beyler et al., 1999). Reasonably accurate predictions were obtained for a set of nine marine fiber reinforced polymer (FRP) composites tested according to ISO 9705.

B.5.11 WPI Model. An enhanced version of Mitler's flame spread algorithms (Mitler and Steckler, 1995) was implemented in CFAST (Peacock et al., 1997) at Worcester Polytechnic Institute (WPI). The model was used to predict room/corner fire test performance of the marine FRP composites tested at SwRI (Beyler et al., 1999).

B.6 Analytical Models.

B.6.1 Magnusson's Model. Thirteen building products were tested in a full ISO 9705 room, a ⅓-scale room, and a number of small-scale tests, including the cone calorimeter. A simple analytical method was developed by Magnusson and Sundström to predict the heat release rate curve in the ISO 9705 room as a function of ignition and heat release rate parameters obtained from analysis of the small-scale data (Magnusson and Sundström, 1984). The heat release rate curve was assumed to be exponentially rising, with a time lag to account for delays associated with room filling and transport of the fire gases from the room to the instrumentation section in the exhaust duct.

B.6.2 Karlsson's Analytical Model. As part of his Ph.D. thesis work, Karlsson also developed an analytical model of the ISO 9705 room/corner test (Karlsson, 1992). This model is a closed-form solution of the wind-aided flame spread equation and is based on the following assumptions:

(1) The heat release rate of the product can be expressed mathematically as an exponentially decaying function of time.
(2) The flame area is a linear function of the heat release rate.
(3) The initial pyrolysis area below the ceiling is a function of the heat output from the burner and the heat released by the product in the corner behind the burner flame.

B.6.3 SP Model. Eleven building products were tested in the ISO 9705 room and in various small-scale tests. This program was conducted in the Nordic countries, and is referred to as the Eurefic program. A semi-empirical calculation method was developed by Wickström and Göransson at the National Testing Institute (SP) in Sweden to estimate the ISO 9705 heat release curve on the basis of ignition time and heat release rate measured in the cone calorimeter at one heat flux level (Wickström and Göransson, 1992).

B.6.4 Dietenberger's Model. Dietenberger, at the Forest Products Laboratory in Madison, Wisconsin, developed an analytical method to predict fire growth in the ISO 9705 room/corner test with material on the walls only (Grexa et al., 1998). The method accounts for errors associated with the dynamic response characteristics of the room/corner test instrumentation, and gives reasonable estimates of the heat release rate measured for 11 untreated wood products, three types of FR-treated plywood, Type X gypsum board, and FR-treated polyurethane foam. A simplified version of the model was published more recently (Dietenberger and White, 2001).

B.7 Extensive validation based on room/corner test data shows that several physics-based models provide reasonably accurate predictions of room/corner tests performance for a wide range of products. Recent efforts using CFD codes to simulate room/corner tests are very promising and indicate that it may become the preferred approach in the very near future (Apte et al., 2004).