NFPA 555

Guide on Methods for Evaluating Potential for Room Flashover

1996 Edition

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National Fire Protection Association, 1 Batterymarch Park, PO Box 9101, Quincy, MA 02269-9101
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This first 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 and acted on by the National Fire Protection Association, Inc., at its Annual Meeting held May 20–23, 1996, in Boston, MA. It was issued by the Standards Council on July 18, 1996, with an effective date of August 9, 1996.

This edition of NFPA 555 was approved as an American National Standard on July 26, 1996.

Origin and Development of NFPA 555

This guide is 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, decreasing its probability.

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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 Appendix A.

Information on referenced publications can be found in Chapter 7 and Appendix B. Detailed information on the references cited in brackets throughout the document can be found in B-1.2.3.

Chapter 1 Introduction

1-1 Scope.

1-1.1 This guide addresses methods for evaluating the potential for room flashover from fire involving the contents, furnishings, and the 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 rate of heat release 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, and use of these principles and concepts can minimize the possibility of flashover but might not prevent it.

1-2 Purpose.

1-2.1 The purpose of this guide is to provide tools for those 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 places significant constraints upon the procedures described in this guide.

1-2.3 Some standard tests under controlled laboratory conditions are described. Such tests should not be deemed to establish performance levels for all situations.

1-3 Instructions for Use of This Guide. See Figure 1-3.

1-3.1 This guide is best used with a proper understanding of the various procedures it contains. Its core consists of five chapters that guide the user through analyses and procedures that are used to determine the likelihood of the compartment under investigation to reach flashover under fire conditions and to minimize the potential for flashover.

1-3.2 After conducting the analysis provided in each chapter, the user can make the determination of 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 chapter.

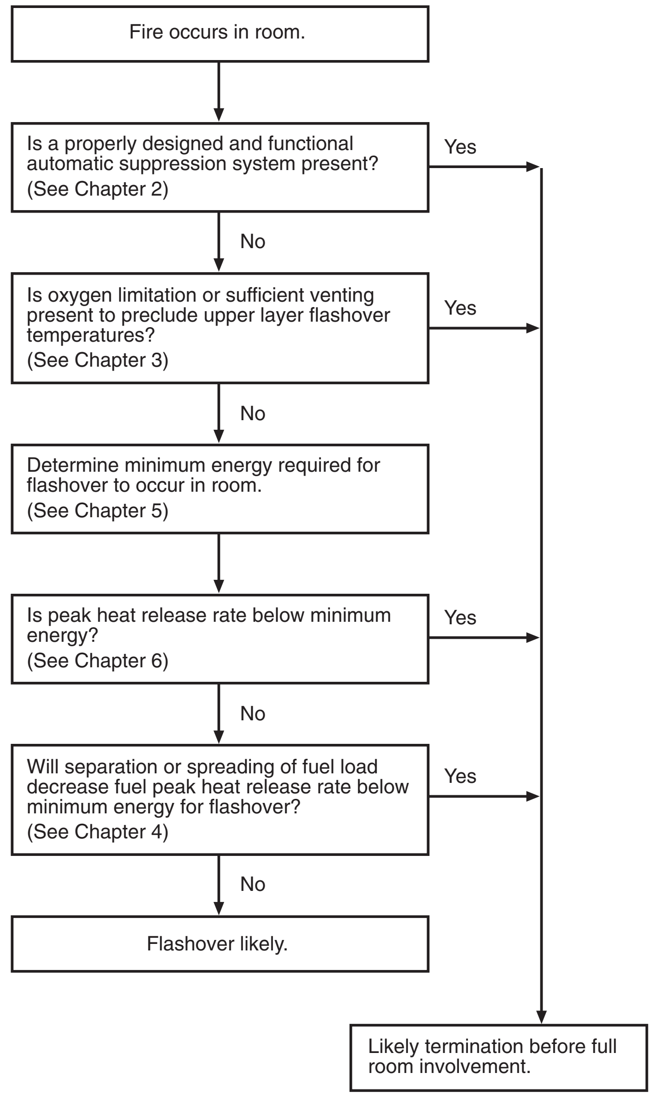


Figure 1-3 Flow chart for use of guide.

1-3.3 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 2 and Chapter 3, respectively. A properly designed and functional system of either kind is likely to be a satisfactory means of reduction of potential for flashover.

1-3.4 If either of the following conditions exists, the user should conduct the analysis specified in Chapters 4 through 6:

(a) There is neither a properly designed and functional automatic suppression system, nor a similarly adequate method of reduction in oxygen availability; or

(b) Added precautions are desired.

1-3.5 Chapter 5 contains techniques for predicting flashover in compartments, irrespective of the contents, furnishings, or interior finishes involved. Chapter 6 indicates how the fire performance of contents, furnishings, or interior finishes can be used to assess the potential for flashover.

Chapter 4 explains how the techniques in Chapter 6 can be expanded to include groups of items or products as fuel packages.

1-4 Definitions.

Contents and Furnishings. Any movable objects in a building that normally are secured or otherwise put in place for functional reasons, excluding the following:

(a) Parts of the internal structure of the building; and

(b) Any items meeting the definition of interior finish.

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. 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 5-1.*)

Fuel Package. A fuel package is a grouping of one or more furnishing 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. 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 4 is solely to facilitate the application of the methods described in Chapter 6 for estimating heat release rates.

Interior Finish. Exposed interior surfaces of buildings, excluding movable items that can be removed when occupants change. 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.

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

Chapter 2 Automatic Suppression Systems

2-1 General. Automatic suppression systems are the most widely used method for automatically controlling a fire. Consideration should be given to the utilization of an automatic suppression system for limiting the fire hazard potential in a room in order to reduce the probability of room flashover.

2-2 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 terminated by the suppression system prior to full room involvement (flashover).

2-3 Hazard Protection. Many standards and guides exist to aid a designer in the development of appropriate automatic suppression system design criteria for a wide range of occupancy types and hazards. Since the range and severity of occupancy types and fire types are rather broad, and since protection goals vary from minimal property protection to large-scale life safety, it is essential that hazards be adequately identified and evaluated and appropriate design guides be employed.

2-4 Automatic Suppression System Evaluation Considerations.

2-4.1 In those cases where a recognized design standard is not the basis for a suppression system design or where 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.

2-4.2 Significant factors affecting the ability of an automatic suppression system 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 above factors might have to be evaluated to establish confidence in the ability of an automatic suppression system to reduce the probability of flashover significantly.

2-5 Design, Installation, and Maintenance. The design, installation, and maintenance of automatic suppression systems are covered by a number of NFPA standards, including:

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

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

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

NFPA 13R, *Standard for the Installation of Sprinkler Systems in Residential Occupancies up to and Including Four Stories in Height.*

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

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

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

Chapter 3 Oxygen Availability and Ventilation

3-1 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.

3-1.2 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 either the amount of 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 the fire and the continued burning of contents, furnishings, or interior finishes in a compartment.

3-1.3 Tightly Closed Compartments. In fire scenarios, where 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, sudden introduction of air (and oxygen) can result in a highly dangerous, rapid combustion of products of incomplete combustion called a backdraft. This might occur when doors are opened or windows are broken in the process of manual fire fighting.

3-1.4 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].

3-2 Oxygen Consumption.

3-2.1 Principle of Oxygen Consumption. It has been determined that the heat released per unit mass of oxygen consumed is nearly constant for most organic fuels. This value can be useful in air-limited fire scenarios to determine if the fire duration or maximum heat release rate predicted to cause flashover can be achieved. The value of heat released per unit mass 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).

3-2.2 Tightly Closed Compartments.

3-2.2.1 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.

3-2.2.2 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 3.1 for steady fires and equation 3.2 for unsteady fires.

Steady Fires:

$$t = \frac{V_{O_2}}{\dot{Q}} \ (\Delta h_c \times \rho_{O_2}) \tag{3.1}$$

Unsteady (t-square) Fires:

$$t = \left(\frac{3\,V_{O_2}}{\alpha} \ (\Delta h_c \times \rho_{O_2})\right)^{1/3} \tag{3.2}$$

where:

t = Time (sec).

V_{O_2} = Volume of oxygen available to be consumed in combustion process [*see 3-2.2.3*] (m^3).

$\Delta h_c \times \rho_{O_2}$ = Heat release per unit mass of oxygen consumed (kJ/m^3).

$\dot{Q}$ = Heat release rate from steady fire (kW).

α = A constant governing the speed of fire growth (kJ/sec^3).

Values of α for typical fire growths are as follows:

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)

The maximum heat release rate for the unsteady (t-square) fire can be estimated as follows in equation 3.3:

$$Q = \alpha\, t^2 \tag{3.3}$$

where t is the time, as determined from equation 3.2. 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.

3-2.2.3 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.

3-2.3 Temperature Rise in Compartment.

3-2.3.1 With the times of fire duration determined from equations 3.1 and 3.2, equation 3.4, 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 if temperature conditions are sufficient for flashover [Milke & Mowrer, 1993].

$$\Delta T = T_0 \ [\exp\,(Q_n/Q_0) - 1] \tag{3.4}$$

3-2.3.2 In equation 3.4, Q_n is the net total heat released, which can be determined from equation 3.5 or 3.6, depending on the type of fire, and Q_o is the total ambient energy of air in the compartment, calculated using equation 3.7.

$$Q_n = (1 - X_L)\,\dot{Q}\,(\Delta t) \qquad \text{(Steady fires)} \tag{3.5}$$

$$Q_n = (1 - X_L)\,\frac{\alpha t^3}{3} \qquad \text{(Unsteady [t-square] fires)} \tag{3.6}$$

$$Q_0 = \rho_0\, c_p\, T_0\, V \tag{3.7}$$

3-2.3.3 Description of Terms.

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/sec3).

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).

3-2.4* Other than the method of analysis outlined using equations 3.1 through 3.7, 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.

3-3 Venting and Exhaust of Hot Smoke Layer.

3-3.1 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 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.

3-3.2 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 92B, *Guide for Smoke Management Systems in Malls, Atria, and Large Areas*, and NFPA 204M, *Guide for Smoke and Heat Venting*.

Chapter 4 Fuel Package Definition

4-1 Introduction. This chapter provides methods for defining a fuel package for use in predicting heat release rates, compartment temperatures, and flashover potential.

4-2 Fuel Package. The two aspects of fuel packages that are discussed in this chapter include the definition of a fuel package and the ignition of a fuel package due to heating by another fuel package within the compartment.

4-3 Defining Fuel Packages.

4-3.1 Guidance. This section includes some simple definitions of fuel packages. These definitions should be used for guidance rather than as strict definitions.

4-3.1.1 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.

4-3.1.2 Items that are far enough away from other items or fuel packages that cannot be ignited by heat transfer from other items or fuel packages are not considered a part of a fuel package.

4-3.1.3 Items that are near enough to other items or fuel packages so 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:

(a) The ignition delay is sufficiently large that the peak heat release rate will have passed before the item reaches its peak burning rate; or

(b) The methods of Chapter 6 cannot be reasonably used if the item is included as part of a nearby fuel package; or

(c) Both 4-3.1.3(a) and (b) apply.

4-4 Methods/Tools.

4-4.1 A set of analytical methods or tools is needed to provide a means for performing the evaluations embodied by the definitions in Section 4-3. 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 section focuses on the radiative ignition of a material not in direct contact with a flame.

4-4.2 Radiative Ignition of Materials.

4-4.2.1* 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 [Quintiere & 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 is less than a critical heat flux, $\dot{q}''_{0,ig}$. 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 as follows by equation 4.1:

$$t_{ig} = \left(\frac{\dot{q}''_{0,ig} / (\dot{q}''_e)}{b} \right)^2 \tag{4.1}$$

where $\dot{q}''_e$ is the incident radiative heat flux and b is related to the thermal properties of the material. This data normally is 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 4-4.2.1 illustrates the ignition behavior of one type of fiberboard using this method [Quintiere& 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.

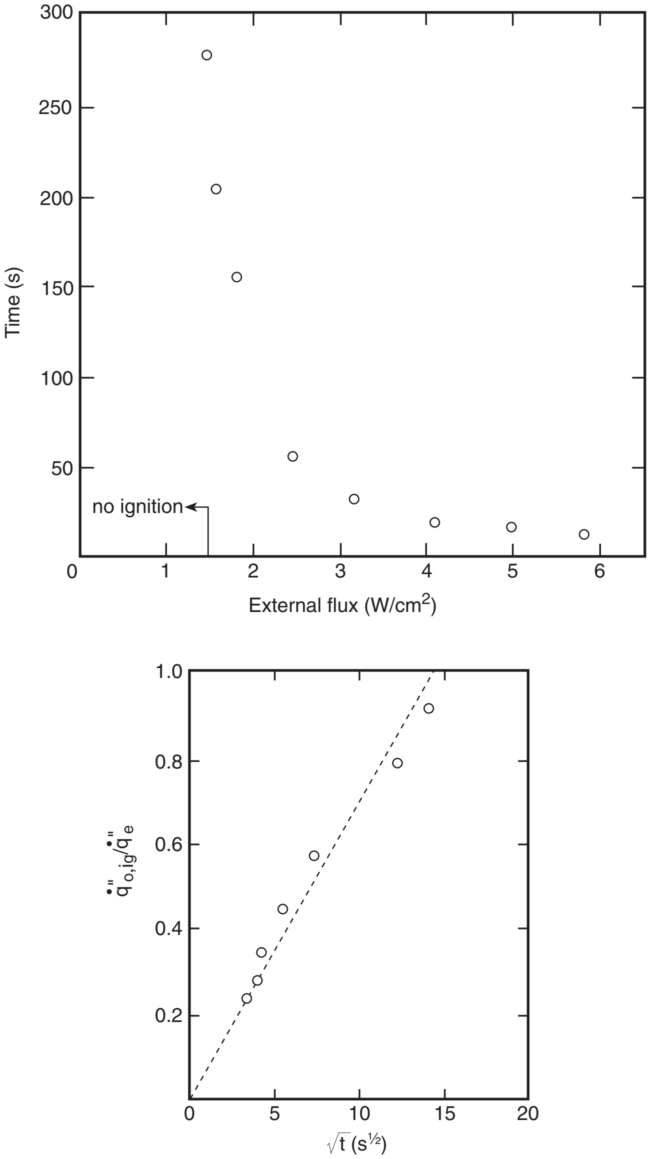


Figure 4-4.2.1 Ignition behavior of a particular type of fiberboard.

4-4.2.2 Equation 4.1 is based on a model of surface temperature (T_s) rise during heating given by equation 4.2 as follows:

$$T_s - T_0 = (\dot{q}''_e / h)\,F(t) \tag{4.2}$$

Where F(t) is determined from equation 4.3 or 4.4 as follows:

$$F(t) = 2ht^{1/2} / (\pi k \rho c)^{1/2} \qquad \text{for } t < t_m \tag{4.3}$$

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

with t_m being the time necessary for equilibration of the surface temperature.

4-4.2.3 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, $\dot{q}''_{0,\ ig}$, is defined by the flux necessary to reach the ignition temperature when $t \geq t_m$. Equation 4.1 is developed from the use of these considerations.

4-4.2.4 The product of the thermal conductivity, k, the density, ρ, and the heat capacity, c, is a fundamental material property often described simply as "kρc." Because of the simplifying assumptions used, the value kρc derived from LIFT (ASTM E 1321, *Standard 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*ρ*c* and should not be expected to be equal to the kρc derived from methods used to measure these heat transfer properties.

4-4.3 Radiative Heating.

4-4.3.1 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 need to be determined. A number of methods can be used to make this determination.

4-4.3.2 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/m², 20 kW/m², and 40 kW/m² are defined as critical flux for ignition of general fuels and are described as easy, normal, and difficult to ignite, respectively. As noted in 4-4.2, the heat flux and duration of radiative exposure determine if ignition can occur.

4-4.3.3 Equations 4.5, 4.6, and 4.7 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:

$$\dot{Q} = 30 \times 10^{\left(\frac{D + 0.08}{0.89}\right)} \tag{4.5}$$

$$\dot{Q} = 30\left(\frac{D + 0.05}{0.019}\right) \tag{4.6}$$

$$\dot{Q} = 30\left(\frac{D + 0.02}{0.0092}\right) \tag{4.7}$$

where:

$\dot{Q}$ = Heat release rate (kW).

D = Distance (m).

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.

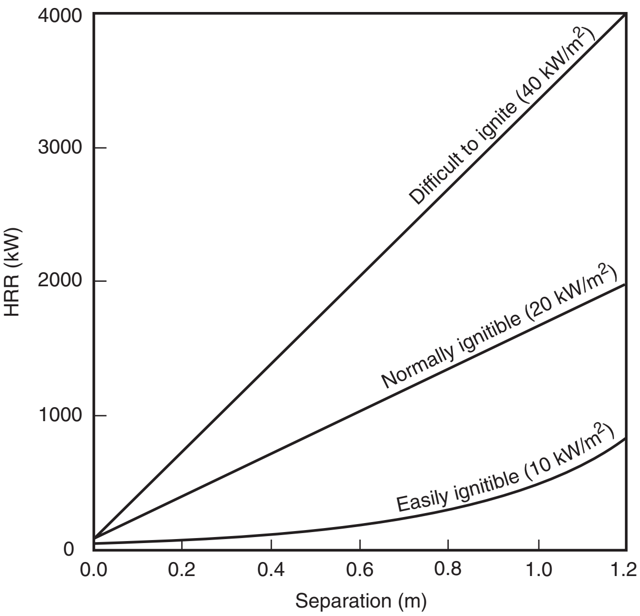


Figure 4-4.3.3.1 The inverse equation — separation distance versus rate of heat release.

4-4.3.3.1 Equations 4.5, 4.6, and 4.7 are plotted in Figure 4-4.3.3.1. This graph can be used as a solution by reading up the appropriate curve to locate the separation distance and then finding the corresponding critical rate of heat release.

4-4.3.3.2 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.

4-4.3.4 Two simple methods for evaluating radiation from pool fires to targets outside the flame have been developed [Mudan & Croce, 1988; Shokri & Beyler, 1989]. While 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 below. 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.

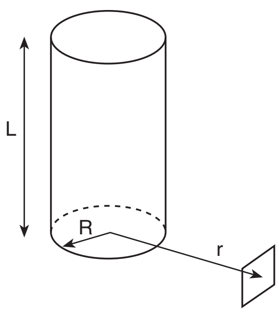
4-4.3.4.1 The radiator is described as a cylinder with a radius determined by the size of the base of the fuel package. The height of the radiator is determined by a flame height correlation. Table 4-4.3.4.1 shows the flame height expressions used in the two models. The emissive powers used in the two models are given in Table 4-4.3.4.1 and are illustrated in Figures 4-4.3.4.1(a) and (b). The radiant flux to the target from the fuel package, $\dot{q}''_{r,\,fp}$, is determined by equation 4.8 as follows:

$$\dot{q}''_{r,\,fp} = F_{fp\text{-}dt}E \tag{4.8}$$

where $F_{fp\text{-}dt}$ is the configuration factor between the cylindrical radiator (fuel package) and the target, and E is the emissive power of the radiator.

Table 4-4.3.4.1 Flame Height and Emissive Power

	Mudan and Croce (1988)	Shokri and Beyler (1989)
Flame Height (m)	$H = 420\left(\dfrac{\dot{Q}}{p_a \Delta H_c \sqrt{gD}}\right)^{0.61}$	$H = 0.23\dot{Q}^{2/5} - 1.02D$ [m,kW]
Emissive Power (kW/m²)	$E = 140\,(e^{-0.12D}) + 20\,(1 - e^{-0.12D})$ [m,kW]	$E = 58\,(10^{-0.00823D})$ [m,kW/m²]



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

where

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

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

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

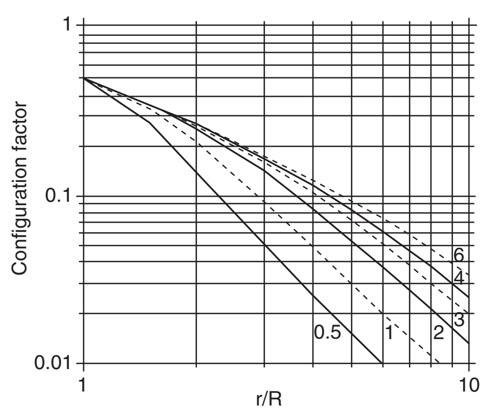


Figure 4-4.3.4.1(a) Configuration factor for a vertical target and a vertical cylindrical radiator ***(adapted from C. L. Beyler).***

4-4.3.4.2 The configuration factors for several relevant geometries are shown in Figures 4-4.3.4.1(a) and (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.

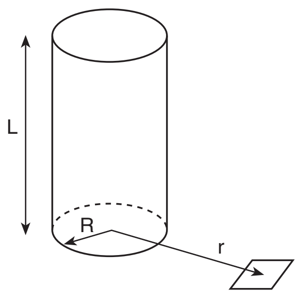
$$F_{d1\text{-}2,H} = \frac{(B - 1/S)}{\pi\sqrt{B^2 - 1}} \tan^{-1}\sqrt{\frac{(B+1)(S-1)}{(B-1)(S+1)}} - \frac{(A - 1/S)}{\pi\sqrt{A^2 - 1}} \tan^{-1}\sqrt{\frac{(A+1)(S-1)}{(A-1)(S+1)}}$$

where

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

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

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



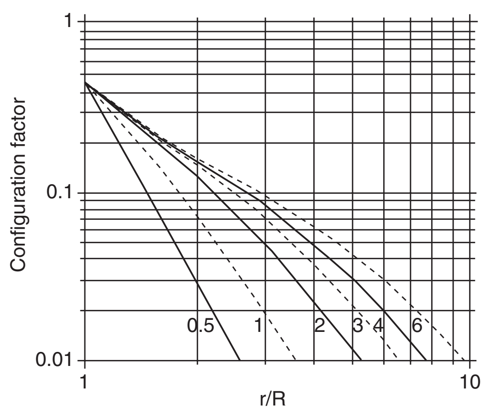


Figure 4-4.3.4.1(b) Configuration factor for a horizontal target and a vertical cylindrical radiator ***(adapted from C. L. Beyler).***

This configuration factor can be created by considering the radiator to be composed of two cylinders, one above the target and one below. Since, 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.

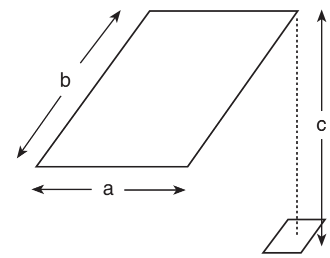
4-4.3.5* The radiation from the hot gas layer can be estimated by methods similar to those described in 4-4.3.4 for the flame. The hot layer radiant can be modeled as a blackbody at the hot gas layer temperature, T_h. The configuration factor between the layer and the target, $F_{hL\text{-}dt}$, can 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 4.9:

$$\dot{q}''_{r,\,h1} = F_{hL-dt}\sigma T_h^4 \tag{4.9}$$

where σ is the Stefan-Boltzmann constant (5.67×10^{-11} kW/m^2 K^4) and T_h is the hot gas layer temperature in Kelvin (°C + 273).

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

where X = a/c and Y = b/c.



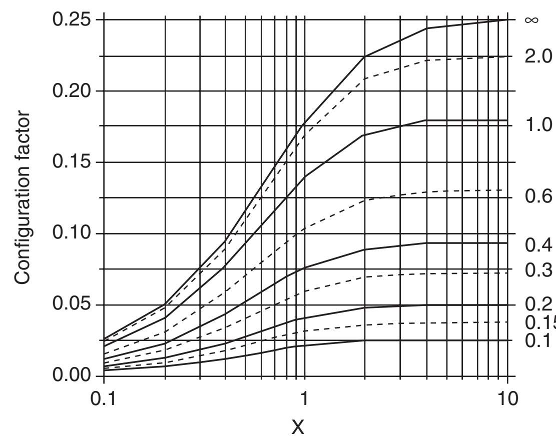


Figure 4-4.3.5(a) Configuration factor for one quadrant of the hot gas layer to a target facing the hot layer ***(adapted from C. L. Beyler).***

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 Figures 4-4.3.5(a) and (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 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).

4-4.3.6 The methods described in Section 4-4 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 section should be taken to exclude the use of better methods than those discussed.

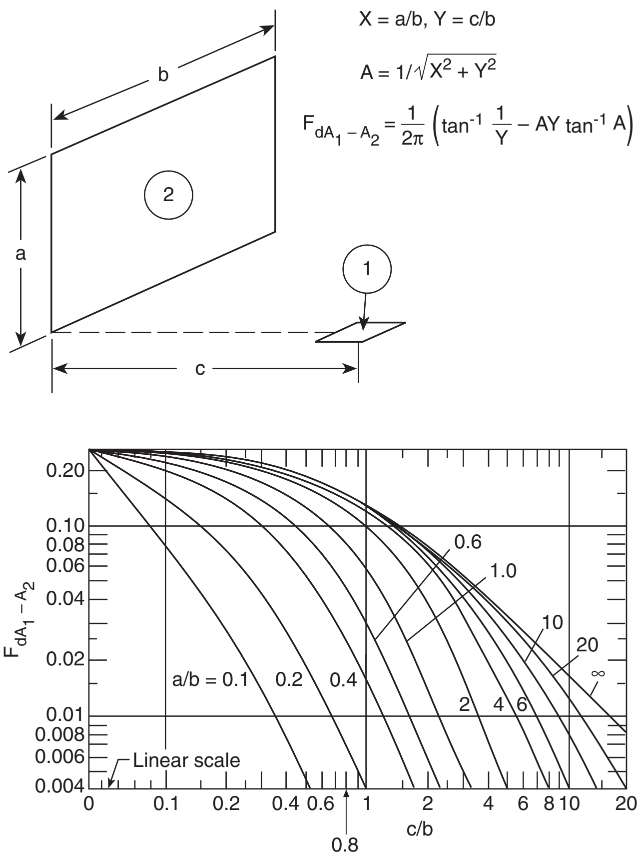


Figure 4-4.3.5(b) Configuration factor for one quadrant of the hot gas layer to a target not facing the hot layer *(adapted from E. M. Sparrow and R. D. Cess)*.

Chapter 5 Predicting Flashover for Fire Hazard Calculations

5-1 Background.

5-1.1 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.

5-1.2* 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.

5-1.3* 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/m² is a reasonable expectation.

5-2 Estimating Room Flashover Potential.

5-2.1* The room flashover potential is best estimated by using Thomas' flashover correlation [Thomas, 1981], as provided in equation 5.1. The constants in equation 5.1 represent values correlated to experiments producing flashover.

$$\dot{Q} = 7.8A_{room} + 378\,(A_{vent}\sqrt{H_{vent}})_{equivalent} \tag{5.1}$$

$$A_{room} = A_{floor} + A_{ceiling} + A_{walls} - (A_{vents})_{equivalent} \tag{5.2}$$

$$W_{vent_{equivalent}} = \frac{\sum_{i=1}^{n} (A_{vent}\sqrt{H_{vent}})i}{\sqrt{H^3_{vent_{equivalent}}}} \tag{5.3}$$

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

$A_{vent} = H_{vent}\,W_{vent}$ (m²)

in which the product, H_{vent} W_{vent}, represents the dimensions of an equivalent vent defined by equation 5.1.

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

$W_{vent\ equivalent}$ equals the 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).

5-2.2* Alternative methods of estimating heat release at flashover also have been developed [Babrauskas, 1980a; Babrauskas & Krasny, 1985; McCaffrey et al., 1981; Quintiere, 1982].

5-2.3* General Information on Thomas' Correlation.

5-2.3.1 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.

5-2.3.2 The fire area should not be subtracted from the floor area since the fire conducts and convects heat into the floor underneath the fuel footprint.

5-2.3.3 The equation is the same, irrespective of the location and 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.

5-2.3.4 The equation does not address the external insulation of the walls. Thus, use of the equation for compartments with thin metal walls might be inappropriate.

5-2.3.5 The equation was developed from tests using fast-growth fires and has not been verified for fires that grow slowly or at moderate rates.

5-2.3.6 The equation was developed from experiments conducted in rooms not exceeding 16 m² in floor area. Extrapolation of the results from this equation for application to rooms with much larger floor areas might not be valid.

5-2.3.7 The equation is not valid for compartments without ventilation, since it would predict the possibility of flashover, which would be unlikely due to oxygen starvation of the fire.

5-2.3.8 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 &

Lee, 1974]. Its validity for other surfaces or fire sources has not been fully established.

Chapter 6 Heat Release Rate Estimation Techniques

6-1 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 6-2 through 6-8 present a hierarchy for the preferred techniques for such estimates.

6-2 Preferred Hierarchical Order.

6-2.1 The preferred hierarchical order indicates that the reliability of the 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 it, with the distances between items and products that are identical to those in the compartment of interest. The applicable techniques are described in more detail in Sections 6-3 through 6-8. The preferred hierarchical order is as follows:

(a) A full compartment fire test, including all items expected to be contained within it;

(b) Full-scale fire tests on individual items;

(c) Tests on large-scale mock-ups of individual items;

(d) Bench-scale tests, using composite samples representative of the end-use composite assemblies;

(e) Bench-scale tests using individual materials rather than composites as samples;

(f) Use of estimation techniques for calculating heat release rate in the compartment as determined from the results of tests in 6-2.1(b) through (e). This might be done by one of the following:

1. Quantitative estimation techniques; or
2. Relative estimation techniques.

6-3 Full Compartment Fire Tests.

6-3.1 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 need to 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.

6-3.2 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.

6-3.2.1 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.

6-3.2.2 If the experiment is being carried out to determine the fire hazard inherent in the compartment being considered, the choice 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.

6-3.2.3 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.

6-3.3 There are some disadvantages in carrying out full compartment fire tests:

(a) They are costly, both in terms of actual expense and in terms of preparation;

(b) They are less susceptible to generalization, since small differences in item or fuel package location can have major effects on fire performance; and

(c) They cannot easily identify the effects of individual items or fuel packages on the overall fire performance of the whole compartment.

6-3.4 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 different 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.

6-4 Full-Scale Tests on Individual Items or Fuel Packages.

6-4.1 General.

6-4.1.1 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 choice 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.

6-4.1.2 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).

6-4.1.3 Where quantitative precision or bias statements have not been developed for the full-scale tests used, appropriate compensation should be made for the lack of information regarding precision or bias.

6-4.1.4 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 7 and Appendix B provide a resource on these subjects.

6-4.1.5* There are nearly an infinite number of material combinations that can be used in the construction of room furnishings. 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 different 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 are limited and do not guarantee low rate of heat release values. Product testing therefore is necessary to determine the heat release rate for any given item.

6-4.2* Wall Finish. Full-scale fire performance of wall finishes can be tested by means of NFPA 265, *Standard Methods of Fire Tests for Evaluating Room Fire Growth Contribution of Textile Wall Coverings*, or ISO 9705, *Fire Tests — Full Scale Room Fire Tests for Surface Products*.

6-4.3 Upholstered Furniture.

6-4.3.1 Full-scale fire performance of upholstered furniture can be tested by means of NFPA 266, *Standard Method of Test for Fire Characteristics of Upholstered Furniture Exposed to Flaming Ignition Source*, or ASTM E 1537, *Standard Test Method for Fire Testing of Real Scale Upholstered Furniture Items*.

6-4.3.2 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 are probably of little consequence in a flashover prevention strategy [Parker et al., 1990].

6-4.4 Mattresses.

6-4.4.1 Full-scale fire performance of mattresses can be tested by means of NFPA 267, *Standard Method of Test for Fire Characteristics of Mattresses and Bedding Assemblies Exposed to Flaming Ignition Source*, or ASTM E 1590, *Standard Test Method for Fire Testing of Real Scale Mattresses*.

6-4.4.2 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 x 3.7 m to 3.1 m x 3.7 m, with a height of 2.5 m. If the heat release rate is that high, the importance of minor effects are probably of little consequence in a flashover prevention strategy.

6-4.5 Other Items.

6-4.5.1 Full-scale fire performance testing of other items should be performed by designing specialized tests for the item under consideration. Similar types of criteria should be developed to those documents referenced in 6-4.2, 6-4.3, and 6-4.4. Items or fuel packages of potential interest include pallets of storage commodities, case goods, and cleaning supplies.

6-4.5.2 It is recommended that ASTM E 603, *Standard Guide for Room Fire Experiments*, be used as a guide for developing the test and for making the measurements.

6-4.5.3 Currently, no standard full-scale fire test exists for floor finish (*see A-6-6.4*). In general, floor finish is not involved in fires until flashover is approached.

6-4.6 The use of tests on individual items has both advantages and disadvantages over testing all components of a compartment.

6-4.6.1 The advantages of testing individual items include:

(a) Lower cost;

(b) Greater specificity on the individual importance of the item under test; and

(c) Easier identification of the effects of composition or construction of the item under test on anticipated fire performance.

6-4.6.2 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.

6-4.7 In order to assess whether the compartment, as configured, is likely to reach flashover, tests should be carried out on all major items and the results should be combined. The simplest way to combine the results is by adding the peak heat release rates obtained from the individual items and comparing them with the predicted heat release rate necessary for flashover as determined from Chapter 5. 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 4-4.3.3*). A further improvement involves the use of an appropriate modeling technique, incorporating experimental fire test data, to predict the potential interactions between the burning items.

6-5 Tests on Large-Scale Mock-ups of Individual Items.

6-5.1 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 Real Scale Upholstered Furniture*

Items). Such tests should be done in the same way as the tests on full-scale products.

6-5.2 This technique does not provide the investigator with an understanding of the effects of construction on fire performance.

6-5.3 Where testing 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]. 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.

6-5.4 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.

6-6 Bench-Scale Tests on Composite Samples.

6-6.1 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 NFPA 264A, *Standard Method of Test for Heat Release Rates for Upholstered Furniture Components or Composites and Mattresses Using an Oxygen Consumption Calorimeter*, or ASTM E 1474, *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.

6-6.1.1 A number of studies have been conducted attempting to relate test results from bench-scale tests to fire performance in full-scale tests and some of these are discussed in the 6-6.1.2 through 6-6.1.8. 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.

6-6.1.2 Estimations of peak heat release rate in the full-scale furniture fire test specified in ASTM E 1537, S*tandard Test Method for Fire Testing of Real Scale Upholstered Furniture Items*, based on cone calorimeter (NFPA 264A, *Standard Method of Test for Heat Release Rates for Upholstered Furniture Components or Composites and Mattresses Using an Oxygen Consumption Calorimeter*, or ASTM E 1474, *Test Method for Determining the Heat Release Rate of Upholstered Furniture and Mattress Components or Composites Using a Bench Scale Oxygen Consumption Calorimeter*) data have been made. The initial work, done cooperatively by NIST and the California Bureau of Home Furnishings, suggested that the average (3-min) heat release rate is capable of predicting full-scale peak heat release rate *(see Figure 6-6.1.2)*. 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. Equation 6.1 determines the non-self-propagating fire region found by that study as follows:

$$\dot{Q}\ (\text{full-scale}) = 0.75 \times \dot{Q}'' \tag{6.1}$$

where $\dot{Q}$ (*full-scale*) is the peak rate of heat release in ASTM E 1537 (in kW), and $\dot{Q}''$ is the average (3-min) heat release rate per unit area in ASTM E 1474 at an incident flux of 35 kW/m^2 [Parker et al., 1990].

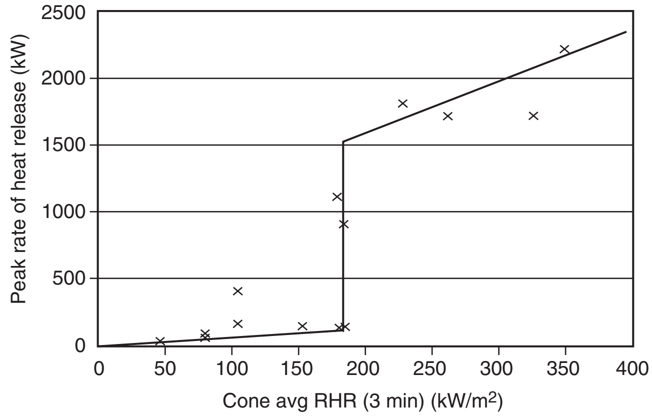


Figure 6-6.1.2 Relation of the results of full-scale ASTM E 1537 upholstered furniture tests with the average rate of heat release from the cone calorimeter (ASTM E 1354), at an incident flux of 35 kW/m^2.

6-6.1.3 Another series of tests was carried out in which nine chairs were tested in ASTM E 1537, *Standard Test Method for Fire Testing of Real Scale Upholstered Furniture Items*, and the systems were also tested in the cone calorimeter (although not following the procedure in ASTM E 1474, *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 6-6.1.3 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].

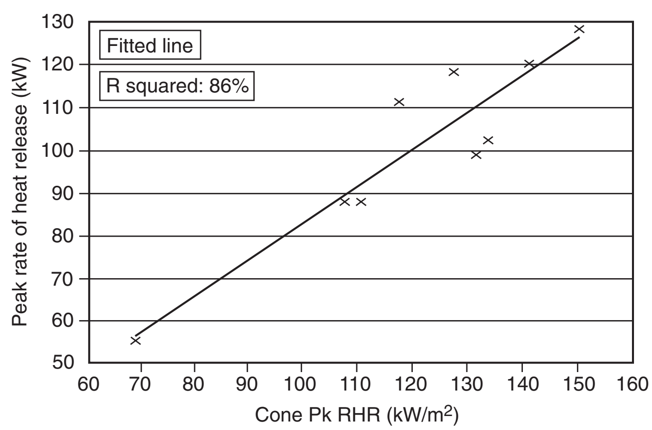


Figure 6-6.1.3 Relation of the results of one series of full-scale ASTM E 1537 upholstered furniture tests with the peak rate of heat release from the cone calorimeter (ASTM E 1354), at an incident flux of 35 kW/m^2. Correlation coefficient: 86%.

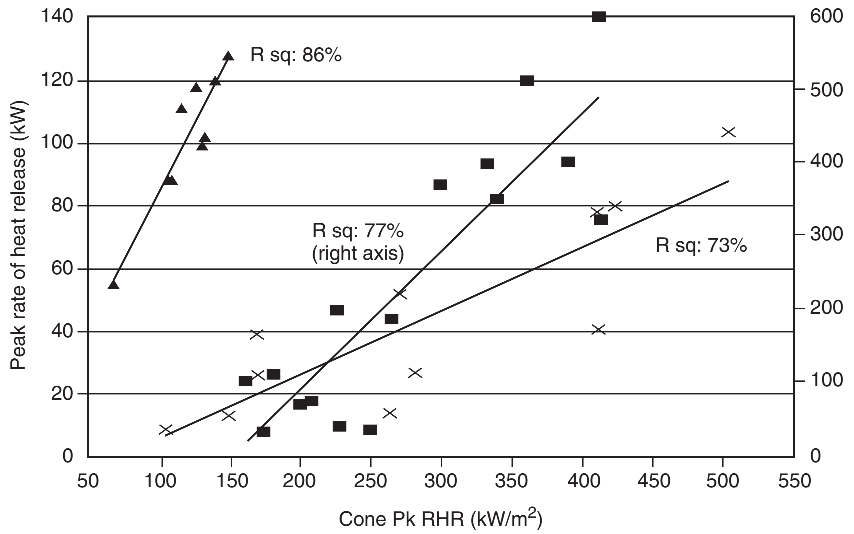


Figure 6-6.1.4 Relation of the results of three series of full-scale ASTM E 1537 upholstered furniture tests with the peak rate of heat release from the cone calorimeter (ASTM E 1354), at an incident flux of 35 kW/m². Correlation coefficients: 86%, 77% and 73%.

6-6.1.4 It should be stated, however, that such estimations are heavily dependent on the systems tested. Figure 6-6.1.4 indicates that, for three separate series of tests, the regressions found, although all linear, corresponded to different linear equations [Hirschler, 1995]

6-6.1.5 Other studies have also been made [Sundstrom, 1995; Forsten, 1995; Ohlemiller and Shields, 1995; ACT/DFA, 1995]. They have shown different types of estimations and have highlighted some difficulties.

6-6.1.6 Other studies in the cone calorimeter using incident heat fluxes of 25 kW/m²[Hirschler and Smith, 1990] and 30 kW/m² [Ames et al., 1993] have also been made.

6-6.1.7* Input from the cone calorimeter (NFPA 264A, *Standard Method of Test for Heat Release Rates for Upholstered Furniture Components or Composites and Mattresses Using an Oxygen Consumption Calorimeter*, or ASTM E 1474, *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 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.

6-6.1.8 Correlation between bench-scale and full-scale test results may be improved by incorporating factors that represent the effects of total mass, frame materials, frame style, and furniture design.

6-6.2 Bedding Materials.

6-6.2.1 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 Real Scale Mattresses* [Babrauskas, 1993].

6-6.2.2 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 those systems with fairly high heat release rate values.

6-6.3 Wall Lining Materials.

6-6.3.1* Several fire models can predict heat release and fire growth of wall linings in a compartment.

6-6.3.2 Standard application procedures for using the cone calorimeter with wall linings have not been fully developed, but some of the issues that need to be resolved regarding mounting techniques have been investigated [Fritz & Hunsberger, 1992].

6-6.4* It has been shown that carpets can be tested in the cone calorimeter (NFPA 264, *Standard Method of Test for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*, or 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/m² to 30 kW/m² [Briggs et al., 1992; Ames et al., 1993; Hirschler, 1992a; Tomann, 1993]. Lower heat fluxes might be more appropriate for testing floor finish products.

6-7 Bench-Scale Tests on Individual Materials.

6-7.1 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.

6-7.2 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.

6-7.3 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*).

6-7.3.1 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 Fire Tests for Surface Products* (options 100 kW and 300 kW; three walls and ceiling covered). It uses input data from the cone calorimeter and equation 6.2, which follows:

$$t_{fo} = k_a \times \frac{t_{ign}\sqrt{\rho}}{\Sigma\, \dot{Q}''_{Pk}} + k_b \tag{6.2}$$

where t_{fo} is the predicted time to flashover in ISO 9705, (in sec), t_{ign} is the time to ignition in the cone calorimeter at an incident flux of 25 kW/m^2 (in sec), ρ is the density (in kg/m^3), $\Sigma\, \dot{Q}''_{Pk}$ is the total heat released per unit area during the peak period in the cone calorimeter at an incident heat flux of 50 kW/m^2, and k_a and k_b are constants [2.76×10^6 J (kg/m)$^{-0.5}$ and –46.0 sec, respectively]. This method has been applied successfully to the Eurefic test data.

6-7.3.2 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 equation 6.3:

$$t_{fo} \propto FPI = \frac{t_{ign}}{Pk\ \dot{Q}''} \tag{6.3}$$

where the t_{ign}, the time to ignition (in sec), is measured in the cone calorimeter at an incident flux that is relevant to the scenario in question, $Pk\ \dot{Q}''$ is the peak heat release rate per unit area at that same incident flux (in kW/m^2), and FPI is the fire performance index (in sec m^2/kW). 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. (*See Figure 6-7.3.2.*)

6-8 Other Prediction Methods.

6-8.1* Several methods exist that can be used as partial predictors of relative adequacy of performance of products and as additional tools.

6-8.2 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.

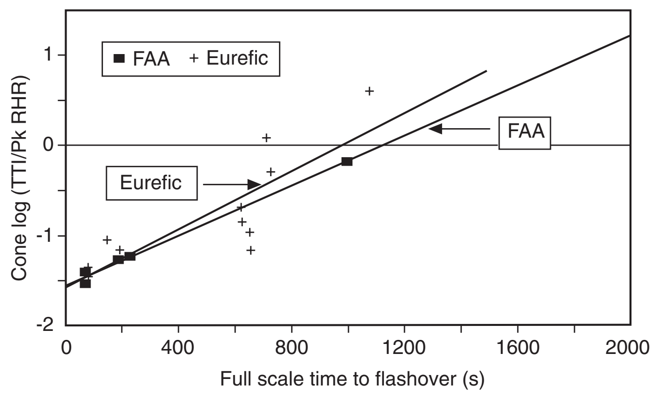


Figure 6-7.3.2 Comparison between full-scale times to flashover for FAA panels within an aircraft and for wall lining materials in ISO 9705, with the ratio of time to ignition to peak rate of heat release in the cone calorimeter (ASTM E 1354) at an incident flux of 50 kW/m^2.

Chapter 7 Referenced Publications

7-1 The following documents or portions thereof are referenced within this guide and should be considered part of the recommendations of this document. The edition indicated for each reference is the current edition as of the date of the NFPA issuance of this document.

7-1.1 NFPA Publications. National Fire Protection Association, 1 Batterymarch Park, P.O. Box 9101, Quincy, MA 02269-9101.

NFPA 12, *Standard on Carbon Dioxide Extinguishing Systems*, 1993 edition.

NFPA 13, *Standard for the Installation of Sprinkler Systems*, 1996 edition.

NFPA 13D, *Standard for the Installation of Sprinkler Systems in One- and Two-Family Dwellings and Manufactured Homes*, 1996 edition.

NFPA 13R, *Standard for the Installation of Sprinkler Systems in Residential Occupancies up to and Including Four Stories in Height*, 1996 edition.

NFPA 17, *Standard for Dry Chemical Extinguishing Systems*, 1994 edition.

NFPA 25, *Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems*, 1995 edition.

NFPA 92B, *Guide for Smoke Management Systems in Malls, Atria, and Large Areas*, 1995 edition.

NFPA 204M , *Guide for Smoke and Heat Venting*, 1991 edition.

NFPA 264, *Standard Method of Test for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*, 1995 edition.

NFPA 264A, *Standard Method of Test for Heat Release Rates for Upholstered Furniture Components or Composites and Mattresses Using an Oxygen Consumption Calorimeter*, 1994 edition.

NFPA 265, *Standard Methods of Fire Tests for Evaluating Room Fire Growth Contribution of Textile Wall Coverings*, 1994 edition.

NFPA 266, *Standard Method of Test for Fire Characteristics of Upholstered Furniture Exposed to Flaming Ignition Source*, 1994 edition.

NFPA 267, *Standard Method of Test for Fire Characteristics of Mattresses and Bedding Assemblies Exposed to Flaming Ignition Source*, 1994 edition.

NFPA 2001, *Standard on Clean Agent Fire Extinguishing Systems*, 1996 edition.

7-1.2 Other Publications.

7-1.2.1 ASTM Publications. American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103-1187.

ASTM E 603, *Standard Guide for Room Fire Experiments*, 1994.

ASTM E 1321, *Standard Test Method for Determining Material Ignition and Flame Spread Properties*, 1993.

ASTM E 1354, *Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*, 1994.

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*, 1992.

ASTM E 1537, *Standard Test Method for Fire Testing of Real Scale Upholstered Furniture Items*, 1994.

ASTM E 1590, *Standard Test Method for Fire Testing of Real Scale Mattresses*, 1994.

7-1.2.2 ISO Publication. International Organization for Standardization, c/o American National Standards Institute, 11 West 42nd Street, New York, NY 10036.

ISO 9705, *Fire Tests — Full Scale Room Fire Tests for Surface Products*, 1991.

7-1.2.3 Bibliography.

ACT/DFA, "Flammability Studies of Selected Fabrics, Flame-Blocking Barriers, and Polyurethane Foams in the California Technical Bulletin 133 and Cone Calorimeter Protocols.Ó The Association of Contract Textiles and Decorative Fabrics Association, 1995.

Ames, S. A., Babrauskas, V., and Parker, W. J., "Upholstered Furniture: Prediction by Correlations," Chapter 15, *Heat Release in Fires*, Elsevier, London, UK, Eds. V. Babrauskas and S. J. Grayson, 519-544 (1992).

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Babrauskas, V., "Will the Second Item Ignite?," *Fire Safety Journal*, 4, 281-292 (1981–82).

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Briggs, P. J., Harris, S. R., Ollerenshaw, M., Van Hees, P., and Van Wesemael, E., "Full Scale Fire Testing of Carpets in Room/Corridor Scenarios and Comparisons with Small Scale Test Procedures," *Flame Retardants 1992*, (Ed. The Plastics and Rubber Institute), Elsevier, London, UK, 297-307, 1992.

Forsten, H. H., "Correlation of CAL 133 with Cone Calorimeter," *Proceedings of the International Conference on Fire Safety*, Volume 20, Ed. Hilado, C., 53-66, 1995.

Fritz, T. W., and Hunsberger, P. L., "Cone Calorimeter Test of Wall Coverings," *Proc. 1st. Int. Conf. on Fire and Materials*, Sept. 24-25, 1992, Crystal City, VA, InterScience Communications, London, UK, 117-123, 1992.

Hinkley, P. L., "Smoke and Heat Venting," Chapter 2-3, *The SFPE Handbook of Fire Protection Engineering*, National Fire Protection Association, Quincy, MA, 2/33-2/44 (1988).

Hirschler, M. M., "Electrical Cable Fire Hazard Assessment with the Cone Calorimeter," *Fire Hazard and Fire Risk Assessment*, ASTM STP 1150, Amer. Soc. Testing and Materials, Philadelphia, PA, Ed. M. M. Hirschler, 44-65 (1992), (1992b).

Hirschler, M. M., "Heat Release from Plastic Materials," Chapter 12a, *Heat Release in Fires*, Elsevier, London, UK, Eds. V. Babrauskas and S. J. Grayson, 375-422 (1992), (1992c).

Hirschler, M. M., "Smoke and Heat Release and Ignitability as Measures of Fire Hazard from Burning of Carpet Tiles," *Fire Safety Journal*, 18, 305-24 (1992), (1992a).

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Hirschler, M. M., and Smith, G. F., "Flammability of Sets of Fabric/Foam Combinations for Use in Upholstered Furniture," *Fire Safety Journal*, 16, 13-31 (1990).

Lyon, R. E., "Fire-Safe Aircraft Materials," *Fire and Polymers Intern. Symp.,* Amer. Chem. Soc. 208th Natl Mtg, Washington, DC, Aug. 21-23, Polymeric Materials: Science & Engineering Div. Preprints, 71, 26-27 (1994).

McCaffrey, B. J., Quintiere, J. G., and Harkleroad, M.F., "Estimating Room Temperatures and the Likelihood of Flashover Using Fire Data Correlations," *Fire Technology*, 17, 2, 98-119 (1981).

Milke, J. A., and Mowrer, F. W., "A Design Algorithm for Smoke Management Systems in Atria and Covered Malls," *Report No. FP93-04*, Univ. Maryland, Dept. Fire Protection Engineering, College Park, MD, May 1993.

Mudan, K. S., and Croce, P. A., "Fire Hazard Calculations for Large Open Hydrocarbon Fires," Chapter 2-4, *The SFPE Handbook of Fire Protection Engineering*, National Fire Protection Association, Quincy, MA, 2/45-2/87 (1988).

Ohlemiller, T. J., and Shields, J. R., "Behavior of Mock-Ups in the California Technical Bulletin 133 Test Protocol: Fabric and Barrier Effects," NISTIR 5653, National Institute of Standards and Technology, Gaithersburg, MD, May 1995.

Parker, W. J., and Lee, B. T., "Fire Build-Up in Reduced Size Enclosures," *Fire Safety Research, Proc. of a Symposium Held at the National Bureau of Standards,*

Gaithersburg, MD on August 22, 1973. Eds. M. J. Butler and J. A. Slater, National Bureau of Standards, Gaithersburg, MD, NBS SP-411, 139-53 (1974).

Parker, W. J., Tu, K. M., Nurbakhsh, S., and Damant, G. H., "Furniture Flammability: An Investigation of the California Technical Bulletin 133 Test. Part III: Full Scale Chair Burns," NISTIR 90-4375, National Institute of Standards Technology, Gaithersburg, MD, 1990.

Quintiere, J. G., "Smoke Measurements: An Assessment of Correlation Between Laboratory and Full-Scale Experiments," *Fire and Materials,* 6, 145-60 (1982).

Quintiere, J. G., and Harkleroad, M. T., "New Concepts for Measuring Flame Spread Properties," *Fire Safety: Science and Engineering,* ASTM STP 882, Ed. T.Z. Harmathy, American Society for Testing and Materials, Philadelphia, PA, 239-269 (1985).

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Thomas, P. H., "Testing Products and Materials for their Contribution to Flashover in Rooms," *Fire and Materials,* 5, 103-11 (1981).

Tomann, J., "Comparison of Nordtest Fire 007, CEN Draft Proposal (Radiant Panel) and Cone Calorimeter Methods in the Fire Testing of Floor Coverings," *Fire and Materials,* 17, 185-90 (1993).

Appendix A Explanatory Material

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

A-3-2.4 The computer-based models are addressed in the following publications:

Bukowski, R. W., Peacock, R. D., Jones, W. W., and Forney, C. L., *Software User's Guide for the HAZARD I Fire Hazard Assessment Method, Volume 1,* NIST HB-1 16/1, National Institute of Standards and Technology, Gaithersburg, MD, 240, June 1989.

Bukowski, R. W., Peacock, R. D., Jones, W. W., and Forney, C. L., *Technical Reference Guide for the HAZARD I Fire Hazard Assessment Method, Volume 2,* NIST HB-1 46/11, National Institute of Standards and Technology, Gaithersburg, MD, 323, June 1989.

Cooper, L. Y., Forney, G. P., and Moss, W. F., *The Consolidated Compartment Fire Model (CCFM) Computer Code Application CCFM VENTS — Part IV; User Reference Guide,* NISTIR 43-15, National Institute of Standards and Technology, Gaithersburg, MD, July 1990.

Mitler, H. E., and Rockett, J. A., *User's Guide to FIRST. A Comprehensive Single-Room Fire Model,* CIB W14/88/22, National Bureau of Standards, Gaithersburg, MD, 1987.

Nelson, H. E., *FPETOOL: Fire Protection Engineering Tools for Hazard Estimation,* NISTIR 4380, National Institute of Standards and Technology, Gaithersburg, MD, 1990.

A-4-4.2.1 Table A-4-4.2.1(a) shows values of the critical heat flux, $\dot{q}''_{0,ig}$, 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-4-4.2.1(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.

A-4-4.3.5 Equation 4.9 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.

A-5-1.2 Temperature. Observations include:

(a) 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, b].

(b) 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 & Heselden, 1972; Heselden, 1973].

(c) 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 [Hågglund 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.

(d) 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].

(e) 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 & Klein, 1978, 1979]. In those tests where there was no full room involvement, 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.

Table A-4-4.2.1(a) Ignition Properties of Materials (Quintiere & Harkleroad, 1985)

Material	$\dot{q}''_{0,ig}$ (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

(f) 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 & Breese, 1979]. For tests where flashover was not obtained, the maximum temperatures achieved were 427°C and 324°C, respectively. The authors note, 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.

(g) 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 where flashover did not occur, temperatures remained below 600°C.

(h) During a series of sixteen 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 & Breese, 1980].

Table A-4-4.2.1(b) Ignition Times of Different Materials in Cone Calorimeter
(All results are the mean of six replications)

Material	Thickness (cm)	Time to Ignition (sec)	Flux (kW/m^2)
Flexible Polyether-Type Polyurethane Foam			
1.2 PCF conv. foam	5.1	11	20
1.5 PCF conv. foam	5.1	22	20
1.8 PCF conv. 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

(i) 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 & Rockett, 1977; Quintiere & 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 sixteen) involving high gas temperatures.

(j) Thomas' semiempirical 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-5-1.3 Heat Flux. Generalizations include:

(a) 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 & 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.

(b) Table A-5-1.3 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 [Smith, date unknown], an unpiloted ignition time of approximately 180 seconds for box cardboard and is close to an ultimate asymptotic value.

Table A-5-1.3 Critical Ignition Heat Flux at a 60-Second Exposure

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

(c) 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 ($^1/_4$-in.) thick fir plywood ignited at 21 kW/m^2 to 33 kW/m^2 [Fang, 1975].

(d) 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].

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

(f) 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 & Breese, 1980].

(g) 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 & 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.

A-5-2.1 Two alternative approaches to that of Thomas [Thomas, 1981] have been proposed to estimate the onset of flashover within a room.

A-5-2.2

(a) The first approach [Babrauskas, 1980a; Babrauskas & 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-5-2.2(a):

$$\dot{Q} = 0.6 A_{vent}\sqrt{H_{vent}} \qquad \text{[A-5-2.2(a)]}$$

where $\dot{Q}$ is the estimated rate of heat release, in MW, A is the door area, in m^2, and H is the door height (in m), with the $A_{vent}\sqrt{H_{vent}}$ product usually designated as the "ventilation factor."

(b) Equation A-5-2.2(a) 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).

(c) Equation A-5-2.2(a) 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 ranges between the results of the following two equations:

$$\dot{Q} = 0.45 A_{vent}\sqrt{H_{vent}} \quad \text{and} \qquad \text{[A-5-2.2(c)1]}$$

$$\dot{Q} = 1.05 A_{vent}\sqrt{H_{vent}} \qquad \text{[A-5-2.2(c)2]}$$

A-5-2.3

(a) 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 over 100 experiments, the correlation found needed two dimensionless quantities, as shown in equation A-5-2.3(a):

$$\Delta T = 480 \left[\frac{\dot{Q}}{\sqrt{g}C_p\rho_0 T_0 A\sqrt{H}}\right]^{2/3}\left[\frac{h_k A_w}{\sqrt{g}C_p\rho_0 A\sqrt{H}}\right]^{-1/3} \qquad \text{[A-5-2.3(a)]}$$

with ΔT in °C, and where ΔT is the temperature rise relative to ambient in °C, h_k is the effective heat transfer coefficient to ceilings/walls, A_w is the effective surface area for heat transfer, including door area, g is the gravitational constant, C_p is the specific heat of gas, ρ_0 is the ambient gas density, and T_0 is the initial ambient absolute temperature. A method for calculating the effective heat transfer coefficient, h_k, ranges has also been published [Pape & Waterman, 1976].

(b) The correlation coefficient between the experimental data and the predictions of equation A-5-2.3(a) 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.

(c) By substituting typical values for C_p, ρ_0, T_0 , and a flashover criterion of $\Delta T = 500°C$, equation A-5-2.3(a) can be reduced to equation A-5-2.3(c) as follows:

$$\dot{Q} = 0.61\ [h_k A_w A\ (h)^{1/2}\ ]^{1/2} \qquad \text{[A-5-2.3(c)]}$$

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

A-6-4.1.5 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 & Walton, 1986; Damant et al., 1989; Smiecinski et al., 1989; Schuhmann & Hartzell, 1989; Hirschler & Smith, 1990; Parker et al., 1990; Damant & Nurbakhsh, 1991; Hirschler & Shakir, 1991; Villa & Babrauskas, 1991; Gallagher, 1992; Barile, 1993; Grand et al., 1994].

A-6-4.2 NFPA *101*®, *Life Safety Code*®, includes some requirements on the use of NFPA 265, *Standard Methods of Fire Tests for Evaluating Room Fire Growth Contribution of Textile Wall Coverings*, while international specifications often reference ISO 9705, *Fire Tests — Full Scale Room Fire Tests for Surface Products*. Comparative details of the tests have been discussed recently [Hirschler, 1994]. The fire performance of wall finish is often assessed according to test results in the Steiner tunnel test (NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials*, or ASTM E 84, *Standard Test Method for Surface Burning Characteristics of Building Materials*). However, the results of this test are not suitable for use in the calculations cited in this document [Belles et al., 1988].

A-6-6.1.7 The Dayton University Furniture Fire Model takes 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*) and uses it 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 & 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 withflame spread: the thermal inertia [$k\rho c$ in units of $(kW/m^2 K)^2$ sec], the ignition temperature T_{ig} in °C, and the flame heating parameter (Φ, in units of kW^2/m^3). It has been shown [Janssens, 1992a] 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 equation A-6-6.1.6 (where T_s is the initial surface temperature in °C):

$$V_p = \frac{\Phi}{k\rho c\,(T_{ig} - T_s)^2} \qquad \text{(A-6-6.1.6)}$$

A-6-6.3.1 The Ohio State University (OSU) model is one of the first comprehensive fire models of a room corner fire, and it was developed at Ohio State University by E. E. Smith [Smith, 1972, 1977, 1978; Smith & Satija, 1983]. It predicts fire growth of wall 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, *Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products*). The model has been shown to be adequate for wood materials but is less satisfactory for some other materials. The two main disadvantages of using this model include:

(a) Work on its development has been virtually discontinued; and

(b) The bench-scale apparatus on which it is based has been somewhat superseded by 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*).

The Eurefic method predicts time to flashover of wall linings as tested in the international room-corner test fire standard (ISO 9705, *Fire Tests — Full Scale Room Fire Tests for Surface Products*, options 100 kW and 300 kW; three walls and the ceiling are covered). Time to flashover also is predicted by the full-scale heat release rate curve as a function of time from the results of the cone calorimeter [ASTM E 1354 or ISO 5660, *Fire Tests — Reaction to Fire — Part 1: Rate of Heat Release from Building Products (Cone Calorimeter Method)*]. This model does not seek any results on factors such as airflow rates and hot layer depths, and it is, thus, a reasonably simple empirical approach. The model is based on three major assumptions:

(a) There is no direct relationship between the burning area growth rate and the heat release rate;

(b) The burning area growth rate is directly proportional to the ease of ignition (i.e., it is inversely proportional to the time to ignition in the cone calorimeter); and

(c) The history of the heat release rate per unit area at each location is the same in full scale as in small scale (cone calorimeter). Unfortunately, the full-scale test model does not have universal approval in the United States, where it is rarely used. The model is also known as the Eurefic model, because it was developed by the European Nordic countries within their particular program of research, with the objective of developing a unified classification system for building products in terms of their fire response characteristics, as a replacement for the various classification systems in existence in individual European countries [Wickström & Göransson, 1987, 1992].

The Lund model also predicts a number of room fire parameters of wall linings, with the same objective as the Eurefic model, and originated at Lund University (Sweden) [Karlsson & Magnusson, 1991, 1992]. It differs from the Eurefic model in a number of ways. First, it uses input from the lateral ignition and spread of flame apparatus (LIFT, ASTM E 1321, *Standard Test Method for Determining Material Ignition and Flame Spread Properties*) as well as from the cone calorimeter (ASTM E 1354 or ISO 5660), while the Eurefic model uses cone data only. Second, it predicts a large number of room fire test variables in addition to heat release rate and time to flashover. Third, this fire model, while based on the same room-corner test for wall linings (ISO 9705), uses a scenario with material on the walls only, rather than on the walls and ceiling. Finally, this model is based on a fundamental, rather than an empirical, approach. The model assumes that the total heat release rate comes from the following five sources:

(a) The gas burner;

(b) The vertical wall area behind the burner flame;

(c) A horizontal strip of material at the ceiling/wall intersection corresponding to the vertical height of the ceiling jet;

(d) The wall material in the upper layer, after flame spread has started; and

(e) The wall linings burning below the hot gas layer.

The model has limited direct applicability, because the test is rarely conducted under the necessary conditions. Nevertheless, the Lund model has greater potential than the Eurefic model, because its fire scenario can be altered with greater flexibility.