# NFPA 92B

# Guide for Smoke Management Systems in Malls, Atria, and Large Areas

# 2000 Edition

NFPA, 1 Batterymarch Park, PO Box 9101, Quincy, MA 02269-9101
An International Codes and Standards Organization

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**NFPA 92B**

**Guide for**

# Smoke Management Systems in Malls, Atria, and Large Areas

**2000 Edition**

This edition of NFPA 92B, *Guide for Smoke Management Systems in Malls, Atria, and Large Areas*, was prepared by the Technical Committee on Smoke Management Systems and acted on by the National Fire Protection Association, Inc., at its World Fire Safety Congress and Exposition™ held May 14–17, 2000, in Denver, CO. It was issued by the Standards Council on July 20, 2000, with an effective date of August 18, 2000, and supersedes all previous editions.

This edition of NFPA 92B was approved as an American National Standard on August 18, 2000.

## Origin and Development of NFPA 92B

The 2000 edition is a substantial rewrite of the document to reflect the best current information on smoke management in malls, atria, and other large spaces. Major changes include new and updated definitions, additional data on the impact of sprinklers on smoke management, extensive discussion on basic principles and limitations, additional information on estimating heat release rates of fires, and new criteria for system verification.

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**Committee Scope:** This Committee shall have primary responsibility for documents on the design, installation, testing, operation, and maintenance of systems for the control, removal, or venting of heat or smoke from fires in buildings.

## Contents

**NFPA 92B**

**Guide for**

# Smoke Management Systems in Malls, Atria, and Large Areas

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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 6 and Appendix F.

## Chapter 1 General Information

**1.1 Objective.** The objective of this guide is to provide owners, designers, code authorities, and fire departments with a method for managing smoke in large-volume, noncompartmented spaces. This guide documents the following:

(1) The problem of smoke movement in indoor spaces
(2) Basic physics of smoke movement in indoor spaces
(3) Methods of smoke management
(4) Data and technology
(5) Building equipment and controls
(6) Test and maintenance methods

**1.2* Scope.** This guide provides methodologies for estimating the location of smoke within a large-volume space due to a fire either in the large-volume space or in an adjacent space. These methodologies comprise the technical basis for assisting in the design, installation, testing, operation, and maintenance of new and retrofitted smoke management systems installed in buildings having large-volume spaces for the management of smoke within the space where the fire exists or between spaces not separated by smoke barriers. Buildings within the scope of this guide include those with atria, covered malls, and similar large-volume spaces. *(See NFPA 92A, Recommended Practice for Smoke-Control Systems, for mechanical smoke control between fire-compartmented building spaces separated by smoke barriers and NFPA 204, Guide for Smoke and Heat Venting, for gravity venting.)* This guide is not intended to apply to warehouses, manufacturing facilities, or other similar spaces. This guide does not provide methodologies to assess the effects of smoke exposure on people, property, or mission continuity.

The algebraic approaches to smoke management contained in this guide all assume the smoke removal will be by mechanical means. In some circumstances, it is possible to remove smoke by gravity venting. The capacity of gravity vents to move smoke through a vent is a function of both the depth and temperature of the hot layer. Procedures for determining the capabilities of gravity venting are contained in NFPA 204, *Guide for Smoke and Heat Venting*. That document, rather than this, should be used to the extent that gravity venting is considered. In general, gravity venting and mechanical venting should not be used in combination for the same space without comprehensive modeling of the situation to ensure that the gravity vents will not lose efficiency or even be reversed by the mechanical venting.

**1.3 Purpose.**

**1.3.1** The purpose of this document is to provide guidance in implementing smoke management systems to accomplish one or more of the following:

(1) Maintain a tenable environment in the means of egress from large-volume building spaces during the time required for evacuation
(2) Control and reduce the migration of smoke between the fire area and adjacent spaces
(3) Provide conditions within and outside the fire zone to assist emergency response personnel in conducting search and rescue operations and in locating and controlling the fire
(4) Contribute to the protection of life and reduction of property loss
(5) Aid in post-fire smoke removal

**1.3.2** Specific design objectives can be established in other codes and standards or by the authority having jurisdiction.

**1.4 Definitions.** For the purposes of this guide the following terms have the meanings given in this chapter.

**1.4.1 Atrium.** A large-volume space created by a floor opening or series of floor openings connecting two or more stories that is covered at the top of the series of openings and is used for purposes other than an enclosed stairway; elevator hoistway; escalator opening; or utility shaft used for plumbing, electrical, air-conditioning, or communications facilities.

**1.4.2* Ceiling Jet.** A flow of smoke under the ceiling, extending radially from the point of fire plume impingement on the ceiling.

**1.4.3* Communicating Space.** A space within a building that has an open pathway to a large-volume space such that smoke from a fire either in the communicating space or in a large-volume space can move from one to another without restriction.

**1.4.4 Covered Mall.** A covered or roofed interior area used as a pedestrian way and connected to a building(s) or portions of a building housing single or multiple tenants.

**1.4.5 End-to-End Verification.** A self-testing method that provides positive confirmation that the desired result (i.e., airflow or damper position) has been achieved when a controlled device has been activated, such as during smoke control, testing, or manual override operations. Failure or cessation of such positive confirmation results in an off-normal indication.

**1.4.6* First Indication of Smoke.** The boundary between the transition zone and the smokefree air. Equations (3) and (4) are used to predict the height of this boundary for smoke filling with no mechanical exhaust operating.

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

**1.4.8* Large-Volume Space.** An uncompartmented space, generally two or more stories in height, within which smoke from a fire either in the space or in a communicating space can move and accumulate without restriction.

**1.4.9 Plugholing.** The condition where air from below the smoke layer is pulled through the smoke layer due to a high exhaust rate.

**1.4.10 Separated Spaces.** Spaces within a building that are isolated from large-volume spaces by smoke barriers that do not rely on airflow to restrict the movement of smoke.

**1.4.11 Smoke.** The airborne solid and liquid particulates and gases evolved when a material undergoes pyrolysis or combustion, together with the quantity of air that is entrained or otherwise mixed into the mass.

**1.4.12 Smoke Barrier.** A continuous membrane, either vertical or horizontal, such as a wall, floor, or ceiling assembly, that is designed and constructed to restrict the movement of smoke. A smoke barrier might or might not have a fire resistance rating. Such barriers might have protected openings.

**1.4.13 Smoke Damper.** A device that meets the requirements of UL 555S, *Standard for Safety Leakage Rated Dampers for Use in Smoke Control Systems*, designed to resist the passage of air or smoke. A combination fire and smoke damper should meet the requirements of UL 555, *Standard for Safety Fire Dampers*, and UL 555S.

**1.4.14 Smoke Layer.** The accumulated thickness of smoke below a physical or thermal barrier. The smoke layer is not a homogeneous mixture, nor does it have a uniform temperature. The calculation methods presented may assume homogeneous conditions. The smoke layer includes a transition zone that is nonhomogeneous and separates the hot upper layer from the smokefree air.

**1.4.15 Smoke Layer Interface.** The theoretical boundary between a smoke layer and the smokefree air, as depicted in Figure A.1.4.6. In practice, the smoke layer interface is an effective boundary within a transition buffer zone, which can be several feet thick. Below this effective boundary, the smoke density in the transition zone decreases to zero. This height is used in the application of Equations (8), (9), (10), and (15).

**1.4.16 Smoke Management System.** An engineered system that includes all methods that can be used singly or in combination to modify smoke movement.

**1.4.17 Stack Effect.** The vertical airflow within buildings caused by the temperature-created density differences between the building interior and exterior or between two interior spaces.

**1.4.18 Tenable Environment.** An environment in which smoke and heat are limited or otherwise restricted to maintain the impact on occupants to a level that is not life threatening.

**1.4.19* Transition Zone.** The layer between the smoke layer interface and the first indication of smoke in which the smoke layer temperature decreases to ambient.

### 1.5 Design Principles.

#### 1.5.1 Fire in Large-Volume Spaces, Malls, and Atria.

**1.5.1.1** Smoke produced from a fire in a large, open space is assumed to be buoyant, rising in a plume above the fire and striking the ceiling or stratifying due to temperature inversion. After the smoke either strikes the ceiling or stratifies, 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. Such smoke filling is represented by 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. Sprinklers can reduce the heat release rate and the air entrainment rate into the plume.

**1.5.1.2** As a result of the zone model approach, the model assumes uniform properties (smoke concentration and temperature) from the point of interface through the ceiling and horizontally throughout the entire smoke layer.

**1.5.1.3** An equilibrium position for the smoke layer interface can be achieved by exhausting the same rate of smoke as is supplied to the smoke layer. Also, smoke exhaust can delay the rate of descent of the smoke layer.

**1.5.1.4** Where the smoke layer has descended to the level of adjacent, occupied spaces, prevention of smoke migration from the atrium or mall to the adjacent spaces can be accomplished by physical barriers or opposed airflow. NFPA 92A, *Recommended Practice for Smoke-Control Systems*, provides guidance on the use of walls to restrict smoke migration. Opposed airflow can be used to restrict smoke migration into open adjacent spaces, with air supplied from within the adjacent space. The required volumetric rate of air supplied to achieve the necessary velocity can be substantial.

**1.5.1.5** For smoke exhaust fans to be effective, makeup air must be provided. Makeup air should be provided at a low velocity. For effective smoke management, the makeup airflow must be sufficiently diffused so as not to affect the flame, smoke plume, or smoke interface. The supply points for the makeup air should be located beneath the smoke interface. The rate of makeup airflow should not exceed the exhaust rate such that the atrium or mall achieves a positive pressure relative to adjacent spaces. If air enters the smoke layer above the interface, it must be accounted for in the exhaust calculations.

**1.5.2 Fires in Communicating Spaces.** Fires in communicating spaces can produce buoyant gases that spill into the large space. The design for this case is analogous to the design for a fire in the large space. However, the design must consider the difference in entrainment behavior between a free plume and a spill plume. If communicating open spaces are protected by automatic sprinklers, the calculations set forth in this guide might show that no additional venting is required. Alternatively, whether or not communicating spaces are sprinklered, smoke can be prevented from spilling into the large space if the communicating space is exhausted at a rate to cause a sufficient inflow velocity across the interface to the large space.

**1.5.3 Detection.** Effective design of smoke management systems requires early detection of the smoke condition.

#### 1.5.4 Fire Suppression Systems.

**1.5.4.1*** Automatic suppression systems are designed to limit the mass burning rate of a fire and will, therefore, limit smoke generation. By limiting the mass burning rate of a fire, smoke generation will be reduced. Fires in sprinklered spaces adjacent to atria and covered mall pedestrian areas can also be effectively limited to reduce the effect on atrium spaces or covered mall pedestrian areas and thus increase the viability of a smoke management system.

**1.5.4.2*** The likelihood of sprinkler activation is dependent on many factors, including heat release rate of the fire and the ceiling height. Thus, for modest fire sizes, sprinkler operation is most likely to occur in a reasonable time in spaces with lower ceiling heights, such as 8 ft (2.4 m) to 25 ft (7.6 m). Activation of sprinklers near a fire causes smoke to cool, resulting in reduced buoyancy. This reduced buoyancy can cause smoke to descend and visibility to be reduced. The equations in Chapter 3 that illustrate smoke filling [(3) and (4)] and production [(8), (9), (10), and (15)] do not apply if a loss of buoyancy due to sprinkler operation has occurred.

**1.5.4.3*** Sprinkler activation in spaces adjacent to an atrium results in cooling of the smoke. For fires with a low heat release rate, the temperature of the smoke leaving the compartment is near ambient, and the smoke will be dispersed over the height of the opening. For fires with a high heat release rate, the smoke temperature will be above ambient and the smoke entering the atrium is buoyant.

**1.5.5 Operating Conditions.** The smoke management system components should be capable of continuous use at the maximum temperatures expected, using the calculations contained in this guide.

**1.5.6 Tenability Analysis.** Where the design of smoke management systems is based on maintaining tenability of a portion of space, one of two approaches can be pursued. First, the design might depend on preventing the development of a smoke layer in that portion of the space. Second, the design might be based on comparing the qualities of a smoke layer to hazard threshold values. Such a demonstration requires that the effects of smoke on people be evaluated. Tenability factors that can be considered include, but are not limited to, the following:

(1) Heat exposure
(2) Smoke toxicity
(3) Visibility

Tenability analysis is outside the scope of this guide. However, other references are available that present analytical methods for tenability analyses [34].

**1.5.7 Egress Analysis.** If the design of the smoke management system design is based on occupants exiting a space before being exposed to smoke or before tenability thresholds are reached, a timed egress analysis must be performed for the space. Timed egress analysis is outside the scope of this guide. However, other references are available that present analytical methods for use in egress analysis [Pauls (1995), Nelson and MacLennan (1995)].

**1.6 Design Parameters.**

**1.6.1 General.** Design criteria should include an understanding with the authority having jurisdiction of the expected performance of the system and the acceptance test procedures.

**1.6.2 Leakage Area.** Design criteria and acceptance testing of smoke management systems should be based on the following considerations with reference to the smoke zone and communicating zones:

(1) Small openings in smoke barriers, such as construction joints, cracks, closed door gaps, and similar clearances, should be addressed in terms of maintaining an adequate pressure difference across the smoke barrier, with the positive pressure outside of the smoke zone *(see NFPA 92A, Recommended Practice for Smoke-Control Systems).*
(2) Large openings in smoke barriers, such as open doors and other sizable openings, can be addressed in terms of maintaining an adequate air velocity through the openings, with the airflow direction into the zone of fire origin.

**1.6.3* Weather Data.** The temperature differences between the exterior and interior of the building cause stack effect and determine the stack effect's direction and magnitude. The stack effect must be considered when selecting exhaust fans. The effect of temperature and wind velocity varies with building height, configuration, leakage, and openings in wall and floor construction.

**1.6.4 Pressure Differences.** The maximum and minimum allowable pressure differences across the boundaries of smoke control zones should be considered *(see NFPA 92A, Recommended Practice for Smoke-Control Systems)*. The maximum door opening forces should not exceed the requirements of NFPA *101*®, *Life Safety Code*®, or local codes and regulations. The minimum pressure difference should be such that there will be no significant smoke leakage during building evacuation. The performance of the system is affected by the forces of wind, stack effect, and buoyancy of hot smoke at the time of fire.

**1.6.5 Summary.** The design objectives contained in Chapter 1 can be met by a variety of methodologies. Some of those methods are further explained in Chapter 2.

## Chapter 2 Design Considerations

**2.1 Basic Considerations.** The selection of various design objectives and methods depends on the protection goals, such as protecting egress paths, maintaining areas of refuge, facilitating fire department access, or protecting property. Consideration needs to be given to the following:

(1) The height, cross-sectional area, and plan area of the large volume to be protected
(2) The type and location of occupancies within and communicating with the large-volume space
(3) Barriers, if any, that separate the communicating space from the large-volume space
(4) Egress routes from the large-volume space and any communicating space
(5) Areas of refuge
(6) Design basis fire used to calculate the smoke production *(see 3.2.5)*. (The analysis should include the type, location, and quantity of fuel; automatic suppression; and ventilation.)

**2.2 Design Methodologies.** Design objectives normally include management of smoke within the large-volume space and any spaces that communicate with the large-volume space. The source of the smoke can be a fire within the large-volume space or within the communicating space. Examples of the design objectives include the following:

(1) Maintaining a tenable environment within all exit access and area of refuge access paths for a sufficient time to allow occupants to reach an exit or area of refuge
(2) Maintaining the smoke layer interface to a predetermined elevation
(3) Allowing fire department personnel to approach, locate, and extinguish a fire
(4) Limiting the rise of the smoke layer temperature and toxic gas concentration, and reduction of visibility

**2.3 Design Limitations.**

**2.3.1 Smoke Accumulation Depth.** The rate of smoke layer descent in a large-volume space is only weakly related to the rate of heat release of the fire. Smoke layer descent, however, is strongly related to the height of the space and the cross-sectional area of the large-volume space involved. Careful calculations using the equations and methodologies in this document are necessary in any situation where the intention is to provide smoke management through the use of an unexhausted volume such as a smoke collection space.

The minimum design depth of the smoke layer is determined by both the thickness (depth) of the ceiling jet and the depth necessary to prevent plugholing. For these reasons, no design should be based on maintaining a smoke layer at a point higher than the level of the ceiling jet or higher than the point of elimination of plugholing, whichever is lower.

The thickness of the ceiling jet has been reported by Beyler [1986] to be in the range of 10 percent to 20 percent of the distance from the source fire to the top of the space.

Plugholing is the condition where air from below the interface is pulled through a relatively shallow smoke layer due to a high exhaust rate at that point. The impact of plugholing can be managed *(see Section 3.9)*.

**2.3.2 Disruption of Smoke Layer Interface.** Any factor that causes increased turbulence in or increased mass flow into the smoke layer or at the interface can affect the smoke layer. Among these factors are the following:

(1) Operation of automatic sprinklers above the smoke layer interface can draw the smoke below the smoke layer interface.
(2) Strong air currents from HVAC systems or elements of the smoke management system discharged near the smoke layer interface can disrupt the interface so as to cause smoke to descend below the smoke layer interface.
(3) Air currents greater than 200 ft/min (61 m/min) striking the rising plume below the interface can cause the plume to bend and increase the rate of entrainment air, causing smoke to descend below the level calculated by the equations in this document. The location of the fuel load, the potential plume from such fuel load, the placement of supply points, and the velocity at the supply points in relation to the plume location need to be analyzed.
(4) Upward thrusting airflows located below the interface and having sufficient momentum to reach the layer can cause turbulent mixing to disrupt the interface and add mass to the smoke layer, causing the layer to descend below the layer interface.
(5) Air forced or induced into the upper layer by means other than the plume will increase the mass in the upper layer, causing the layer to descend below the design depth unless compensated for in the smoke management system design.

**2.3.3 Special Considerations Related to Natural Venting.**

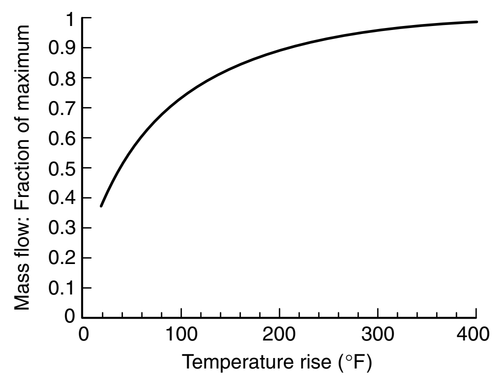
The capability of buoyant forces to move smoke through a natural vent is a function of both the depth and temperature of the hot layer. The gravity-induced mass flow through vents increases with increasing depth and increasing temperature. The methodology for assessing the mass flow through a vent is contained in NFPA 204, *Guide for Smoke and Heat Venting*.

Normally, natural and mechanical venting are incompatible with each other if they serve the same air volume. There is significant potential for a short circuit of the airflow whereby the natural vents are reversed in flow direction to become the source of air for the mechanical vents. Any design that considers such a mix of venting methods needs careful engineering analysis or physical (scale) modeling to ensure that the design will function as intended.

Potential environmental wind conditions, including consideration of the impact of any nearby portions of the building or nearby structures that can cause down drafts, need to be evaluated in any design dependent on natural vents.

The mass of smoke is only weakly related to the rate of heat release of the fire, whereas changes in smoke layer temperature are almost directly related to the rate of heat release. Consequently, a fire that is significantly smaller than the design fire will produce only a low-temperature smoke layer, with less mass flow than that of the design fire. However, less flow is necessary to provide venting for the smaller fire. Figure 2.3.3(a) is an evaluation of the efficiency of mass flow through a vent where the indoor air temperature is the same as the outdoor temperature. The figure is formulated by keeping all parameters constant except the temperature rise of the smoke layer.

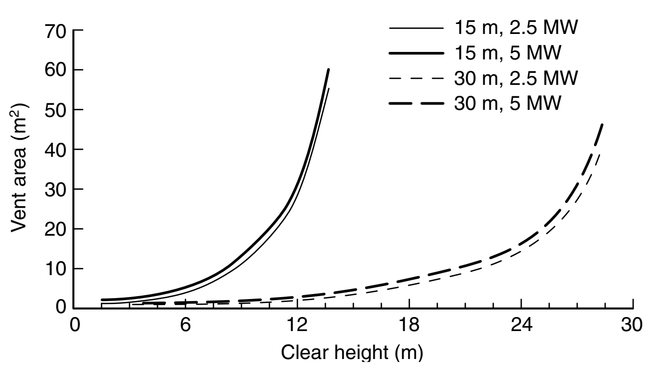
**FIGURE 2.3.3(a) Mass flow efficiency through a vent.**




Although Figure 2.3.3(a) indicates an appreciable reduction in the efficiency of a natural vent, with small fires producing a modest increase in smoke layer temperature, a small fire also produces less smoke, thereby requiring less venting. Milke and Klote [1998] evaluated the effect of different heat outputs of fires on the vent area that is needed to maintain a particular clear height. This analysis indicates that the required vent area is relatively insensitive to the heat output of the fire.

Figure 2.3.3(b), from the analysis by Milke and Klote [1998], depicts vent areas required to maintain various smoke interface layer heights for given fire sizes and ceiling heights.

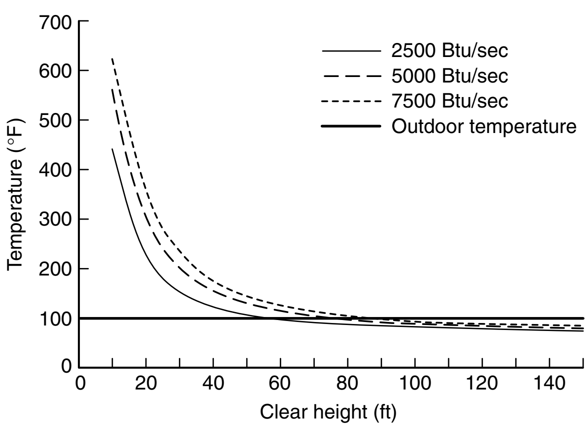
**FIGURE 2.3.3(b) Vent area required to maintain clear height.**



The effectiveness of natural vents can be appreciably reduced or eliminated where the outdoor air temperature is high. One scenario of particular concern involves a fire occurring in a space with an indoor temperature that is lower than the outdoor temperature (i.e., summer conditions with an air-conditioned atrium). While the smoke might be buoyant relative to the indoor air and rise to the ceiling, once the vent opens, outdoor air will enter the building if the outdoor air temperature is higher than that of the smoke layer. As such, no smoke will be exhausted and the smoke layer interface can descend.

An example of the limitations of natural vents due to outdoor temperature is indicated in Figure 2.3.3(c). In this example, an outdoor temperature of 100°F (38°C) is assumed. The smoke layer temperature versus clear height is determined by the equation for temperature rise ($\Delta T$) in the upper layer for a vented fire *(see Table 3.5)*, for three fires with different heat release rates. Where the smoke layer temperature is less than the outdoor temperature, no exhaust is expected. As such, natural venting is not a viable method of smoke management for a 2500-Btu/sec (78-kW) fire for which the intended clear height is greater than 60 ft (18 m). Similarly, clear heights greater than 80 ft and 90 ft (24 m and 27 m) cannot be achieved with natural venting for the 5000-Btu/sec and 7500-Btu/sec (155-kW and 233-kW) fires.

**FIGURE 2.3.3(c) Limitations of natural vents due to outdoor temperature.**




**2.4 Design Approaches.** The design options available for the design of smoke management depend on the space in which the smoke is to be managed and the space in which smoke originates, as described in 2.4.1 and 2.4.2. The design method, if any, for removing smoke from a space (mechanical exhaust versus natural venting) or for containing smoke to a space (airflow method versus pressurization method) needs to be considered.

**2.4.1 Management of Smoke in a Large-Volume Space.** A number of acceptable methods exist for managing smoke from a fire originating in a large-volume space. Table 2.4.1 summarizes the basic design considerations for each of these methods, which include the following:

(1) Utilizing the large-volume space as a smoke reservoir and modeling smoke layer descent to determine whether the smoke layer interface reaches a height at which occupants are exposed to smoke before they are able to egress from the space

(2) Removing smoke from the large-volume space, using a mechanical exhaust capacity sufficient to maintain the smoke layer interface at a predefined height in the space for an indefinite period of time

(3) Removing smoke from the large-volume space, using a mechanical exhaust capacity that slows the rate of smoke layer descent for a period that allows occupants to safely egress from the space

(4) Providing natural venting sufficient to maintain the smoke layer interface at a predefined height in the space for an indefinite period of time

(5) Providing natural venting sufficient to slow the rate of smoke layer descent for a period that allows occupants to safely egress from the space

Only algebraic calculation methods are discussed with regard to each of the design approaches listed in Table 2.4.1. Scale modeling, compartment fire models (zone models), or computational fluid dynamics (CFD) models can be used to demonstrate each as outlined elsewhere in this document.

**Table 2.4.1 Smoke Control Methods for Large-Volume Space**

| Approach | Design Fire | Algebraic Methods for Smoke Transport Calculations | People Movement Calculations |
|---|---|---|---|
| Smoke filling vs. timed egress analysis | Steady | Eq. (3) | Necessary |
| | Unsteady fire | Eq. (4) | Necessary |
| Mechanical smoke exhaust to achieve constant layer height† | Steady | Eq. (8),(9), (10), (15) | Not necessary |
| Mechanical smoke exhaust vs. timed egress analysis | Steady | Eq. (8),(9), (10), (15) | Necessary |
| | Unsteady fire | Eq. (8),(9), (10), (15) | Necessary |
| Natural venting with constant layer height† | Steady | See NFPA 204 | Not necessary |
| Natural venting vs. timed egress analysis | Steady | See NFPA 204 | Necessary |
| | Unsteady fire | See NFPA 204 | Necessary |

†An unsteady fire is not an option for this approach because only a steady fire results in a constant layer height.

**2.4.1.1 Smoke Filling Versus Timed Egress Analysis.** A method for removing smoke from a large-volume space is not necessarily needed if it can be demonstrated that occupants are able to egress the space safely before the smoke layer descends to the point at which the occupants are exposed to the smoke. Exposure can be in terms of presence of smoke or tenability of the environment to which occupants are exposed.

A conservative estimate of the position of the smoke layer is the first indication of smoke, as shown in Figure A.1.4.6, and as calculated using the empirically derived Equations (3) and (4) in Section 3.6. Equation (3) applies to steady fires, and Equation (4) applies to unsteady fires, as defined in Section 3.2. Equations (3) and (4) implicitly account for the transport lag associated with the movement of smoke from the fire into the upper layer.

Equation (3) cannot be combined with Equation (4) to calculate layer descent for growing fires with a steady-state maximum. Each of these equations is empirically derived and cannot be used in combination with the other. Calculation of layer descent for growing fires with a steady-state maximum should be accomplished in a manner similar to that described in 2.4.1.3.

**2.4.1.2 Smoke Exhaust to Achieve Constant Layer Height.** A timed egress analysis need not be performed if it can be shown that the smoke layer interface is maintained at a height so as to not expose occupants to smoke for an indefinite period of time. Constant layer height is accomplished if an exhaust capacity equal to the volumetric production of smoke at the design layer interface height is provided. Stated otherwise, the volume of smoke being introduced into the smoke layer is equal to the volume of smoke being removed by the mechanical exhaust. In general, this method applies strictly to steady fires, unless the peak volumetric smoke production is known for an unsteady fire over the design period of smoke management system operation. The volumetric smoke production rate at a given layer interface height can be calculated using Equations (8), (9), (10), and (15). The temperature of the smoke entering the layer, calculated using the equations in Table 3.5, need to be accounted for in calculating the smoke density used in Equation (22).

Because Equations (8), (9), (10), and (15) reference an interface height corresponding to the top of the transition zone shown in Figure A.1.4.6, a design interface height needs to be selected that ensures that occupants are not exposed to smoke. When selecting this design interface height, the expected depth of the transition zone needs to be considered.

Exposure can be in terms of presence of smoke or tenability of the environment to which occupants are exposed.

**2.4.1.3* Smoke Exhaust Versus Timed Egress Analysis.** Smoke exhaust can be used to slow the rate of smoke layer descent for a period that allows occupants to safely egress from a space. This approach can be used where it is not possible to provide an exhaust capacity sufficient to maintain smoke at a design interface layer for an indefinite period of time. To calculate the smoke layer position over time, a transient analysis needs to be performed that takes into account the change in smoke production as a function of the position of the smoke layer interface as well as the smoke removal provided by a mechanical smoke exhaust system. This approach is discussed in detail in A.2.4.1.3. Equations (8), (9), (10), and (15) are used to determine the volumetric input of smoke into the smoke layer for a given time step. A specified quantity of mechanical smoke exhaust is then removed from the smoke layer over the same time step. The new layer position at the end of the time step is then calculated. The temperature of the smoke entering the layer, calculated using the equations in Table 3.5, must be accounted for in calculating the smoke density used in Equation (22). Transport lag associated with the movement of smoke from the fire into the upper layer might or might not be included in this analysis. Ignoring transport lag yields a more conservative result as the smoke is instantaneously added to the upper layer, resulting in a more rapid layer descent. The transport lag may be appreciable when considering fires in spaces with large areas.

Because Equations (8), (9), (10), and (15) reference an interface height corresponding to the top of the transition zone shown in Figure A.1.4.6, a design interface height needs to be selected that ensures that occupants are not exposed to smoke. When selecting this design interface height, the expected depth of the transition zone needs to be considered.

Exposure can be in terms of presence of smoke or tenability of the environment to which occupants are exposed.

**2.4.1.4 Natural Venting to Achieve Constant Layer Height.** For some applications, natural venting can be used to maintain the smoke interface at a specific height indefinitely. This can be accomplished if the amount of smoke vented is equal to the volumetric production of smoke at the design layer interface height. The mechanical exhaust option discussed in 2.4.1.2 applies strictly to steady fires, unless the peak volumetric smoke production is known for an unsteady fire over the design period of smoke management system operation. The volumetric smoke removal provided by natural venting can be calculated using methods outlined in NFPA 204, *Guide for Smoke and Heat Venting*.

**2.4.1.5 Natural Venting Versus Timed Egress Analysis.** Natural venting can be used for some applications in a manner similar to that specified in 2.4.1.3 so as to slow the rate of smoke layer descent for a period that allows occupants to safely egress from a space. This approach can be used where it is not possible to provide mechanical exhaust or natural venting of sufficient capacity to maintain smoke at a design interface layer for an indefinite period of time. To calculate the smoke layer position over time, a transient analysis needs to be performed that takes into account the change in smoke production as a function of the position of the smoke layer interface as well as the smoke removal provided by natural venting. A similar approach is discussed in detail for mechanical exhaust *(see A.2.4.1.3)*. The volumetric smoke removal provided by natural venting can be calculated using methods outlined in NFPA 204, *Guide for Smoke and Heat Venting*.

**2.4.1.6 Management of Smoke Spread to Communicating Spaces.** Management of smoke spread to communicating spaces can be accomplished by one of the following methods:

(1) Maintaining the smoke layer interface at a level higher than that of the highest opening to the communicating space
(2) Providing a smoke barrier to limit smoke spread into the communicating space (A pressure difference might need to be applied across the smoke barrier.)
(3) Providing an opposed airflow over the face of the opening to prohibit smoke spread into the communicating space
(4) Prompting suppression of the fire to terminate the development of a heated smoke plume

**2.4.1.6.1** Smoke exhaust can be provided within the large-volume space to limit the depth of smoke accumulation, or increase the time for smoke filling within the large-volume space, so that the smoke layer interface remains above the level of the highest opening to communicating spaces for the time necessary to achieve the design objectives.

**2.4.1.6.2** Smoke barriers can be provided to limit smoke spread into the communicating space. Depending on the extent of openings in the barrier, a pressure difference might need to be applied across the smoke barrier. This method is discussed in NFPA 92A, *Recommended Practice for Smoke-Control Systems*. A pressure difference can be achieved by exhausting the large-volume space so that it is at a negative pressure with respect to the communicating space. This method, with some limitations for use in a large-volume space, is discussed in NFPA 92A. A pressure difference can also be provided by supplying air to the communicating space.

**2.4.1.6.3** The airflow method can be used to prevent smoke movement from the large-volume space into communicating spaces for large openings where the pressurization method is impractical. The airflow method employs a face velocity across the entire opening. Section 3.13 provides a calculation method for determining the minimum face velocity to be provided. This method is also applicable for adjacent spaces below the smoke layer interface, for limiting smoke spread to those spaces by lateral smoke spread from intersecting plumes. When using the airflow method, the flow should be nearly perpendicular to the plane of the opening.

**2.4.2 Management of Smoke Within Communicating Spaces.**

**2.4.2.1 Fire in Spaces Surrounding a Large-Volume Space.** Possible configurations for the relationship between the large-volume space and the surrounding spaces include the following:

(1) Separated space
(2) Communicating space

**2.4.2.2 Fire in Separated Spaces.** Where construction separating the large-volume space from the surrounding areas is sufficiently tight so that the pressure differences between the fire zone and the nonfire zones can be controlled, the large-volume space can be treated as one of the zones in a zoned smoke-control system. *(Zoned smoke-control systems are described in NFPA 92A, Recommended Practice for Smoke-Control Systems.)*

**2.4.2.3 Fire in Communicating Spaces.** Communicating spaces can be designed to allow the smoke to spill into the large-volume space. In this instance, the smoke spilling into the large-volume space should be handled by the smoke management system, which is provided to maintain the design smoke layer interface height. Communicating spaces can also be designed to prevent the movement of smoke into the large-volume space. Such a design would require sufficient exhaust from the communicating space so as to establish a minimum flow between it and the large-volume space.

**2.4.2.3.1 Exhaust Through a Large-Volume Space.** For fires in unsprinklered spaces, the exhaust rate from the large-volume space needs to be evaluated not only for a free plume from a fire in the large-volume space but also for a plume originating in the communicating space. The smoke management system should be able to handle either condition, but not both simultaneously. The methods for calculating the volumetric smoke production for spill plumes and window plumes are discussed in 3.8.2 and 3.8.3, respectively. The equations in 3.8.2 and 3.8.3 are valid only for fires in unsprinklered spaces, since they were derived empirically from test data. Once smoke enters the large-volume space, the possibility of the smoke curling back onto upper floors or impinging on overhanging ceilings of upper floors exists and should be considered. There is a possibility that this smoke will enter upper floors of communicating spaces, and the hazard this smoke might present to these spaces should be evaluated.

**2.4.2.3.2 Containment of Smoke to Communicating Spaces.**

Communicating spaces can also be designed to prevent the movement of smoke into the large-volume space. Such a design would require sufficient exhaust from the communicating space so as to establish a minimum flow between it and the large-volume space. The face velocity across the face area of the opening that achieves this is described in 2.4.1.6.3, and Chapter 3 provides calculation methods for smoke generation in the communicating space. The exhaust quantity necessary for this situation can greatly exceed the capacity of the normal building HVAC systems and can require the installation of a dedicated smoke management system for the communicating space.

The placement of the exhaust openings should be evaluated carefully. Exhaust intake and discharge openings should be located so that smoke movement will not interfere with exits. The location of the exhaust discharge to the outside should be located away from outside air intakes to minimize the likelihood of smoke being recirculated. Smoke barriers can also be provided between the large-volume space and communicating spaces. If construction separating the large-volume space from the surrounding areas is sufficiently tight so that the pressure differences between the fire zone and the nonfire zones can be controlled, the large-volume space can be treated as one of the zones in a zoned smoke-control system. Zoned smoke-control systems are described in NFPA 92A, *Recommended Practice for Smoke-Control Systems.*

**2.4.3 Consideration of Tenability in Smoke Management System Design.** The options for smoke management system design discussed in 2.4.1 and 2.4.2 are based on the objective of maintaining smoke layers at sufficient heights for periods of time that prevent exposure of occupants to the effects of smoke. Smoke management systems can, in some cases, be designed to anticipate contact of occupants with smoke, as long as basic tenability conditions are ensured. Tenability conditions that can be considered in the analysis include the following:

(1) Visibility distance
(2) Smoke toxicity
(3) Smoke temperature

The determination of smoke toxicity usually includes the analysis of exposure to carbon monoxide (CO). Exposure to other fuel-dependent toxic gases can also be considered. Tenability limits for both smoke toxicity and smoke temperature usually consider the time of exposure to the smoke.

The calculations pertaining to the determination of visibility distance are discussed in A.3.5. An evaluation of the effects of smoke on people due to smoke toxicity and smoke temperature is outside the scope of this guide. However, as stated in 1.5.6, other references are available that present analytical methods for tenability analyses [34].

**2.5 Smoke Management System Operation.**

**2.5.1 General.** Smoke management systems for large-volume spaces are intended to restrict the smoke layer to the upper portion of the large-volume space or to limit the amount of smoke from spreading to areas outside the large-volume space. The following events need to occur to accomplish these goals.

(1) The fire needs to be detected early (before the smoke level or rate of descent exceeds the design objectives). If the smoke management system is provided to assist safe evacuation, occupant reaction time to the emergency and evacuation time should be considered.
(2) The HVAC system serving the large-volume space and communicating spaces needs to be stopped if its operation would adversely affect the smoke management system.
(3) Smoke should be removed from the large-volume space above the desired smoke layer interface.
(4) Sufficient makeup air should be provided to satisfy the exhaust. It is essential that the makeup air supply inlet and the exhaust outlet be separated so that the contaminated air is not drawn into the building.

**2.5.2 Automatic Activation.** The configuration of the large-volume space should be considered in selecting the type of detector to be used to activate the smoke management system. The size, shape, and height of the space need to be evaluated. These factors vary widely among atrium designs and need to be considered carefully in selecting detectors for a large-volume space. In addition, the envelope of the large-volume space needs to be evaluated for its contribution to temperature stratification. The height of the large-volume space and its architectural features, such as skylights, are dominant factors in determining stratification.

**2.5.2.1** Environmental factors, such as convection currents and mechanical air movement, also need to be considered in selecting detector type and location. *(See NFPA 72, National Fire Alarm Code®, for guidance on selecting detectors.)* The automatic activation of the smoke management system can be initiated through the following means:

(1) Spot-type smoke detectors
(2) Beam-type smoke detectors
(3) Automatic sprinkler system waterflow
(4) Other detectors found to be suitable
(5) Combinations of the above

**2.5.2.2** Normally, all automatic detection devices within the large-volume space and communicating spaces should activate the smoke management system. Detectors for special purposes, such as elevator recall and door release, and for specific hazards, such as special fire-extinguishing systems, can be exceptions. To avoid unnecessary operation of the system from smoke detector activation, consideration should be given to activating the system by two or more smoke detectors or on alarm verification.

Automatic detection devices should not be connected directly to the smoke management system without further concern for the integrity of the detection system. Integrity of the detection system is addressed in NFPA 72, *National Fire Alarm Code*.

**2.5.2.3** Spot-type smoke detectors can be used on or near low ceilings of large-volume spaces, provided that the detectors are accessible for servicing and positioned based on consideration of the effects of stratification and air currents caused by natural and mechanical forces.

**2.5.2.4** Projected beam-type smoke detectors can be used on or near high ceilings of large-volume spaces and positioned to project the beam horizontally or in other acceptable orientations. Stratification and natural or mechanical air currents can necessitate the use of additional projected beams at interim levels of the large-volume space where ceiling heights would contribute to a delay in initiating smoke management.

**2.5.2.5** Automatic sprinkler waterflow should also be used to activate the smoke management system. It is important that the sprinkler system be zoned with the smoke detection system in the large-volume space so that the correct smoke management response is effected. The height of the large-volume space and the location of sprinklers should be analyzed in order to estimate sprinkler activation response time. Sprinkler activation time can be too slow to effectively initiate smoke management where sprinklers are located several stories above the floor of the space. The equations of Chapter 3 should be used to analyze each case. Sprinkler waterflow should nevertheless be one of the smoke management system initiating means, even if only as a backup system. Sprinkler activation can provide an effective primary initiation means where sprinklers are located on lower ceilings.

**2.5.3 Manual Control.** A means of manually starting and stopping the smoke management system should be provided at a location accessible to the fire department.

**2.6 Smoke Management System Reliability.**

**2.6.1 Fault Analysis.** Every smoke management system should be subjected to a fault analysis to determine the impact of a failure, improper operation, or partial operation of each major system component on intended system operation. Of particular concern are those systems that are intended to maintain a pressure or flow balance between adjacent spaces to control the movement of smoke. If it is found that the faulty operation of a component will cause reversal of the smokeflow or lowering of the smoke interface layer to dangerous levels, the degree to which its operation can be reduced and the probability of such occurrence should be determined.

**2.6.2 Reliability.** Reliability of the smoke management system depends on the specific reliability of individual components, functional dependence of the components on one another, and degree of redundancy. Reliability of the individual components (i.e., hardware, software, and interfaces with other systems) involves both their performance during normal operating conditions as affected by environmental factors over the life of the system and their ability to withstand the stresses endured during a fire. Typically, such a component review is conducted in the evaluation of those components by an independent testing laboratory. However, listing/classification of components is not sufficient to ensure their reliability. Also, the impact of the functional dependence of the components on one another cannot be readily examined by the evaluation of individual components. A total systems reliability analysis is needed. Frequent maintenance and testing are also needed to assess the system reliability throughout the life of the system. Supervision of the system components enhances the reliability of the system by providing a timely visual or audible indication of component failure and facilitates prompt repair.

**2.6.3 Periodic Testing.** Periodic testing is essential to ensure that the system is operational and will reliably perform when needed. Means should be provided for performing periodic tests of the smoke management system to verify the system performance. Systems should be designed to permit testing without any special equipment other than what is provided with the system. Because access for performance verification measurements is often difficult, it is desirable that, where possible, instrumentation be completely or partially built-in and partially provided as portable monitors.

## Chapter 3 Calculation Procedures

**3.1 Introduction.**

**3.1.1 Design Approaches.** Three different approaches to smoke management system design are described as follows:

(1) Scale modeling using a reduced scale physical model following established scaling laws, whereby small-scale tests are conducted to determine the requirements and capabilities of the modeled smoke management system
(2) Algebraic, closed-form equations derived primarily from the correlation of large- and small-scale experimental results
(3) Compartment fire models using both theory and empirically derived values to estimate conditions in a space

Each approach has values and limitations. None is totally satisfactory. Although the results obtained from the different approaches should normally be similar, they are not usually identical. The state of the art while advanced, is empirically based, and a final theory provable in fundamental physics has not yet been developed. The core of each calculation method is based on the entrainment of air (or other surrounding gases) into the rising fire-driven plume. A variation of approximately 20 percent in entrainment occurs between the empirically derived entrainment equations commonly used, such as those indicated in this chapter, or in zone-type compartment fire models. Users might wish to add an appropriate safety factor to exhaust capacities to account for this uncertainty. A brief discussion of the values of the several approaches follows.

**3.1.1.1 Scale Modeling.** Scale modeling is especially desirable where the space being evaluated has projections or other unusual arrangements that prevent a free-rising plume. In a scale model, the model is normally proportional in all dimensions to the actual building. The size of the fire and the interpretation of the results are, however, governed by the scaling laws, as given in 3.1.2. Although sound, the approach is expensive, time-consuming, and valid only within the range of tests conducted. Because this approach is usually reserved for complex structures, it is important that the test series cover all of the potential variations in factors such as position and size of fire, location and capacity of exhaust and intake flows, variations in internal temperature (stratification or floor–ceiling temperature gradients), and other variables. It is likely that detection will not be appraisable using scale models.

**3.1.1.2 Algebraic Equations.** Algebraic equations, as contained in this guide, provide a desktop means of calculating individual factors that collectively can be used to establish the design requirements of a smoke management system. The equations presented are considered to be the most accurate, simple, algebraic expressions available for the proposed purposes. In general, they are limited to cases involving fires that burn at a constant rate of heat release ("steady fires" as described in 3.2.2) or fires that increase in rate of heat release as a function of the square of time ("unsteady fires" as described in 3.2.3). The equations are not appropriate for other fire conditions or for a condition that initially grows as a function of time but then, after reaching a maximum, burns at a steady state. In most cases, judicious use of the equations can reasonably overcome this limitation. Each of the equations has been derived from experimental data. In some cases, the test data are limited or have been collected within a limited set of fire sizes, space dimensions, or points of measurement. Where possible, comments are included on the range of data used in deriving the equations presented. It is important to consider these limits.

Caution should be exercised in using the equations to solve the variables other than the ones presented to the left of the equal sign, unless it is clear how sensitive the result is to minor changes in any of the variables involved. If these restrictions present a limit that obstructs the users' needs, consideration should be given to combining the use of equations with either scale or compartment fire models. Users of the equations should appreciate the sensitivity of changes in the variables being solved.

**3.1.1.3* Compartment Fire Models.** Computer capabilities sufficient to execute some of the family of compartment fire models are widely available. All compartment fire models solve the conservation equations for distinct regions (control volumes). Compartment fire models can be generally classed as zone models or computational fluid dynamics (CFD) models.

**3.1.1.3.1 Zone Models.** Zone models are the simpler models and can usually be run on personal computers. Zone models divide the space into two zones, an upper zone that contains the smoke and hot gases produced by the fire and a lower zone, which is the source of entrainment air. The sizes of the two zones vary during the course of a fire, depending on the rate of flow from the lower to the upper zone, the rate of exhaust of the upper zone, and the temperature of the smoke and gases in the upper zone. Because of the small number of zones, zone models use engineering equations for heat and mass transfer to evaluate the transfer of mass and energy from the lower to the upper zone, the heat and mass losses from the upper zone, and other features. Generally, the equations assume that conditions are uniform in each respective zone.

In zone models, the source of the flow into the upper zone is the fire plume. All zone models have a plume equation. A few models allow the user to select among several plume equations. Most current zone models are based on an axisymmetric plume.

Because present zone models assume that there is no preexisting temperature variation in the space, they cannot directly handle stratification. Zone models also assume that the ceiling smoke layer forms instantly and evenly from wall to wall. This fails to account for the initial lateral flow of smoke across the ceiling. The resulting error can be significant in spaces having large ceiling areas.

Zone models can, however, calculate many important factors in the course of events (for example, smoke level, temperature, composition, and rate of descent) from any fire that the user can describe. Most zone models will calculate the extent of heat loss to the space boundaries. Several models calculate the impact of vents or mechanical exhaust, and some predict the response of heat- or smoke-actuated detection systems.

**3.1.1.3.2 CFD Models.** CFD models, also referred to as field models, usually require large-capacity computer workstations or mainframe computers and advanced expertise to operate and interpret. CFD models, however, can potentially overcome the limitations of zone models and complement or supplant scale models.

As with zone models, CFD models solve the fundamental conservation equations. In CFD models, the space is divided into many cells (or zones) and use the conservation equations to solve the movement of heat and mass between the zones. Because of the massive number of zones, CFD models avoid the more generalized engineering equations used in zone models. Through the use of small cells, CFD models can examine the situation in much greater detail and account for the impact of irregular shapes and unusual air movements that cannot be addressed by either zone models or algebraic equations. The level of refinement exceeds that which can usually be observed or derived from scale models.

**3.1.2 Scaling Laws.**

**3.1.2.1*** In this guide, the emphasis of scaling activities is placed on modeling hot gas movement through building configurations due to fire. Combustion and flame radiation phenomena are ignored. Fire growth is not modeled. A fire needs to be specified in terms of a steady or time-varying heat release rate.

**3.1.2.2*** Based on the relationships in Table 3.1.2.2, a scale model can be developed. The model should be made large enough to achieve turbulent flow of the full-scale system. Scaling expressions relating full-scale conditions *(F)* to those in a scale model *(m)* are presented in Table 3.1.2.2, assuming that the same ambient conditions exist.

**Table 3.1.2.2 Scaling Expressions**

| | |
|---|---|
| Geometric position | $x_m = x_F\ (l_m/l_F)$ |
| Temperature | $T_m = T_F$ |
| Pressure difference | $\Delta p_m = \Delta p_F\ (l_m/l_F)$ |
| Velocity | $v_m = v_F\ (l_m/l_F)^{1/2}$ |
| Total heat release rate | $Q_m = Q_F\ (l_m/l_F)^{5/2}$ |
| Convective heat release rate | $Q_{c,m} = Q_{c,F}\ (l_m/l_F)^{5/2}$ |
| Volumetric exhaust rate | $V_{fan,m} = V_{fan,F}\ (l_m/l_F)^{5/2}$ |
| Thermal properties of enclosure | $(k\rho c)_{w,m} = (k\rho c)_{w,F}\ (l_m/l_F)^{0.9}$ |

where:
$c$ = specific heat of enclosure materials (wall, ceiling)
$k$ = thermal conductivity of enclosure materials (wall, ceiling)
$l$ = length
$\Delta p$ = pressure difference
$Q$ = heat release rate
$t$ = time
$T$ = temperature (ambient and smoke)
$v$ = velocity
$V$ = volumetric exhaust rate
$x$ = position
$\rho$ = density
$c$ = convective
$F$ = full-scale
$m$ = small-scale model
$w$ = wall

**3.1.3 Algebraic Equation-Based Calculations.** The remainder of this chapter presents the algebraic equation-based calculation procedures for the various design parameters, as referred to in the previous sections. The calculation procedures represent an accepted set of algebraic equations and related information available for this edition of the guide.

**3.1.4 Establishment of Two-Layer Environment.** A delay in activating exhaust fans can allow smoke to descend below the design height of the smoke interface. Initial smoke accumulation at low levels can also be aggravated by initial vertical temperature stratifications that delay transport of smoke to the upper reaches of the large volume space. However, with the exhaust and air makeup systems activated, a clear lower layer can be expected to develop in agreement with the design assumptions.

**3.1.5 SI Units.** SI forms of the equations contained in this chapter are presented in Appendix D.

**3.2 Design Fire.**

**3.2.1* General.** All the design calculations presented in this guide are dependent on the heat release rate from the fire. Thus, as a first step, the design fire size needs to be identified. The design fire size is determined based on an engineering analysis of the characteristics of the fuel, the effects induced by a fire, or both. In addition, fires can be considered as steady or unsteady.

**3.2.2 Steady Fires.** A steady fire is defined as a fire with a constant heat release rate. As such, the fire is expected to grow quickly to some limit. Further extension is restricted either due to fire control activities (manual or automatic) or a sufficient separation distance to neighboring combustibles being present.

**3.2.2.1* Effect of Sprinklers on Fire Size.** Unless there is reason to expect that fire will continue to spread after sprinkler activation, the effect of sprinklers on the design fire size can be accounted for by assuming that the fire stops growing when sprinklers are actuated. In other words, the design fire is the estimated fire size at the moment of sprinkler actuation. It is assumed that the fire continues to burn at this size until the involved fuel is consumed, with no further effect of the sprinkler spray on the burning process. Alternatively, if fire tests indicate the fire will be controlled but not immediately extinguished by the sprinklers, an exponential decrease in heat release rate can be assumed. However, if tests for the prevailing ceiling height show that fire in the combustible material will be quickly suppressed with the installed sprinkler protection, combustion can be assumed to essentially cease when the sprinklers operate.

**3.2.2.2 Separation Distance.** The design fire should be determined by considering the type of fuel, fuel spacing, and configuration. The selection of the design fire should start with a determination of the base fuel package, the maximum probable size fuel package likely to be involved in fire. The design fire should be increased if other combustibles are within the separation distance, *R*, indicated in Figure 3.2.2.2(a) and determined from Equation (1). Note that, if the base fuel package is not circular, an equivalent radius needs to be calculated by equating the floor area covered by the fuel package with that subtended by a circle of the equivalent radius. The entire floor area covered or included between commodities should be considered in the calculations. For example, if the fuel package consists of the furniture items illustrated in

Figure 3.2.2.2(b), the area of the fuel package would include that covered by the furniture as well as the area between the furniture items.

$$R = \left(\frac{Q}{12\pi q''}\right)^{1/2} \quad (1)$$

where:

$R$ = separation distance from target to center of fuel package (ft)
$Q$ = heat release rate from fire (Btu/sec)
$q''$ = incident radiant heat flux required for nonpiloted ignition (Btu/ft$^2$·sec)

**FIGURE 3.2.2.2(a) Separation distance, *R*.**

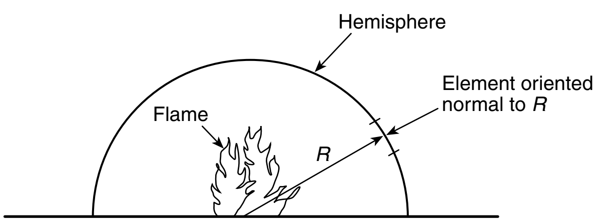
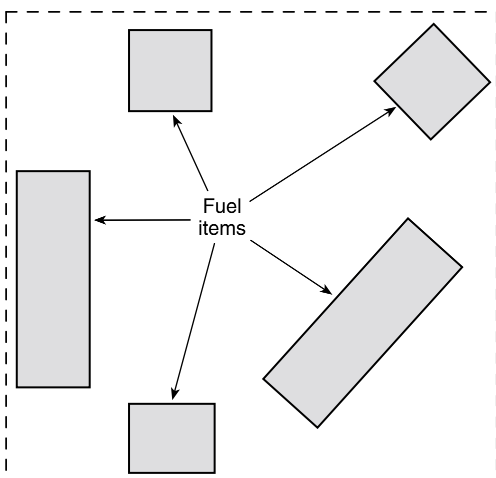



**FIGURE 3.2.2.2(b) Fuel items.**




**3.2.2.3 Design Fire Size.** Specification of a fixed design fire size applicable to all situations is not realistic. The type and amount of fuel should be considered when determining the design fire size. Further, a standard size design fire cannot be recommended, due to the lack of available data in North America to indicate that the design fire is only exceeded in a limited proportion of cases, including either atria or covered malls.

**3.2.3 Unsteady Fires.** An unsteady fire is one that varies with respect to time. A *t*-squared profile is often assumed for unsteady fires. Then, the heat release rate at any time is given by Equation (2):

$$Q = 1000\left(\frac{t}{t_g}\right)^2 \quad (2)$$

where:

$Q$ = heat release rate from fire (Btu/sec)
$t$ = time after effective ignition (sec)
$t_g$ = growth time (sec)

The growth time is the time interval from the time of effective ignition until the fire exceeds 1000 Btu/sec. See Appendix C for further information on *t*-squared profile fires.

Due to the dynamics of secondary ignitions, a *t*-squared profile can be used for engineering purposes until large areas become involved. Thus, a *t*-squared profile is reasonable until the fire growth is limited either by fire control activities or a sufficient separation distance to neighboring combustibles to prevent further ignition. After this time, it is assumed that the fire does not increase in size.

**3.2.4 Data Sources for Heat Release Rate.**

**3.2.4.1** Recently, a limited amount of heat release rate data for some fuel commodities have been reported (NFPA 204, *Guide for Smoke and Heat Venting*, and Babrauskas and Krasny (1985)). *(See Appendix B.)* However, furniture construction details and materials are known to substantially influence the peak heat release rate, such that heat release rate data are not available for all furniture items or for "generic" furniture items.

**3.2.5 Minimum Design Fire Size Caution.**

**3.2.5.1** The selected design fire size should represent a credible worst-case scenario. Designers and analysts are strongly cautioned against selecting modest fire sizes based solely on the type or limited amount of combustibles that are present or expected.

**3.2.5.2** In low ceiling spaces [ceiling height less than 25 ft (7.6 m)] in which sprinklers are provided, the design fire consists either of a steady design fire or a fire that grows to some steady threshold size, for example, due to operation of an automatic suppression system.

**3.2.5.3** In high ceiling spaces [ceiling height at least 25 ft (7.6 m)] in which sprinklers are not present or their operation is expected to be appreciably delayed, the design fire can consist either of a steady design fire or a fire that grows to some steady threshold size. The heat release rate for the steady phase of the design fire should be at least 2000 Btu/sec (2110 kW). Design fires with smaller heat release rates rely on strict fuel control and maintenance of separation distances and ignore daily or seasonal "temporary" uses or modifications of the space.

**3.3 Fire Detection and Sprinkler Actuation.** The response of fire detectors and sprinklers mounted under the ceiling can be estimated from the temperature rise generated by the fire at those locations. The temperature rise depends on the vertical distance above the base of the fire and the radius from the fire centerline axis. NFPA 72, *National Fire Alarm Code*, provides a procedure for determining heat detector spacing [for heights less than 30 ft (9 m)] based on the size and growth rate of the fire to be detected, various ceiling heights, and ambient temperatures. The underlying theories, assumptions, limitations, and known and potential sources of errors for estimating the response time of smoke and heat detectors are identified and discussed in Schifiliti and Pucci (1996). An engineering analysis is needed for ceiling heights greater than 30 ft (9 m).

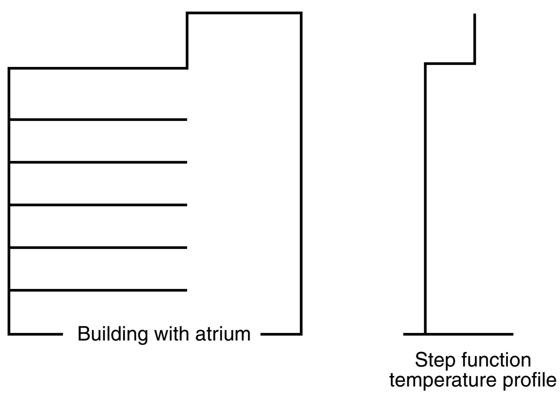
**3.4* Stratification of Smoke.**

**3.4.1 General.** The potential for stratification relates to the difference in temperature between the smoke and surrounding air at any elevation (Morton et al. (1956)). The maximum height to which plume fluid (smoke) rises, especially early after ignition, depends on the convective heat release rate and the ambient temperature variation in the open space.

Of particular interest are those situations when the temperature of the air in the upper portion of the large open space is greater than at lower levels before the fire. This can occur as a result of a solar load where the ceiling contains glazing materials. Computational methods are available to assess the potential for intermediate stratification.

One case of interest is depicted in Figure 3.4.1. In this case, the temperature of the ambient air is relatively constant up to a height above which there is a layer of warm air at uniform temperature. This situation can occur if the upper portion of a mall, atrium, or other large space is unoccupied so that the air in that portion is left unconditioned.

**FIGURE 3.4.1 Pre-fire temperature profile.**




**3.4.2 Step Function Temperature.** If the interior air has a discrete temperature change at some elevation above floor level, the potential for stratification can be assessed by applying the plume centerline temperature correlation. If the plume centerline temperature is equal to the ambient temperature, the plume is no longer buoyant, loses its ability to rise, and stratifies at that height.

**3.4.3 Impact of Stratification of Smoke on Smoke Management System Design.** Once a smoke evacuation system has started in an atrium or other large space, the stratification condition will be eliminated by removal of the hot layer. The problem facing the designer is how to ensure that the presence of smoke is promptly detected through all potential pre-fire temperature profiles. Under some conditions, such as nights and cold days, it is probable that a stratification condition will not be present and any smoke plume will promptly rise to the roof or ceiling of the volume, in which case detection at or near the top of the volume would be responsive. In other cases, such as hot summer days or days with a high solar load, the plume might not reach the top of the volume and the smoke can spread at a level lower than intended, in which case detection near the top of the volume would not respond and the smoke management system would not be started. There is no sure way of identifying what condition will be present at the start of a fire. Any of the following detection schemes can provide for prompt detection regardless of the condition present at the time of fire initiation:

(a) *An Upward Beam to Detect the Smoke Layer.* The purpose of this approach is to quickly detect the development of a smoke layer at whatever temperature condition exists. One or more beams are aimed at an upward angle to intersect the smoke layer regardless of the level of smoke stratification. For redundancy when using this approach, more than one beam smoke detector is recommended.

(b) *Horizontal Beams to Detect the Smoke Layer at Various Levels.* The purpose of this approach is to quickly detect the development of a smoke layer at whatever temperature condition exists. One or more beam detectors are located at the ceiling. Additional detectors are located at other levels lower in the volume. The exact positioning of the beams is a function of the specific design but should include beams at the bottom of any identified unconditioned (dead-air) spaces and at or near the design smoke level with several intermediate beam positions at other levels.

(c) *Horizontal Beams to Detect the Smoke Plume.* The purpose of this approach is to detect the rising plume rather than the smoke layer. For this approach, an arrangement of beams close enough to each other to assure intersection of the plume is installed at a level below the lowest expected stratification level. The spacing between beams is based on the narrowest potential width of the plume at the level of detection.

**3.5* Smoke Layer Properties.** Equations to calculate the smoke layer depth, average temperature rise, optical density, and species concentrations during the smoke filling stage and the quasi-steady vented stage are provided in Table 3.5. These equations apply to fires with constant heat release rates and *t*-squared fires. These equations can also be used to calculate the conditions within the smoke layer once the vented conditions exist.

**3.6* Height of First Indication of Smoke at Any Time.**

**3.6.1 General.** The position of the first indication of smoke at any time can be determined from the relations in 3.6.2 and Section 3.7. The relations address the following three situations:

(1) No smoke exhaust is operating *(see 3.6.2)*.
(2) The mass rate of smoke exhaust equals the mass rate of smoke supplied from the plume to the smoke layer *(see 3.7.1)*.
(3) The mass rate of smoke exhaust is less than the rate of smoke supplied from the plume to the smoke layer *(see 3.7.2)*.

**Table 3.5 Equations for Calculating Properties of Smoke Layer**

| Parameters | Unvented Fires: Steady Fires | Unvented Fires: $t$-squared Fires | Vented Fires |
|---|---|---|---|
| $\Delta T$ | $T_o\{[\exp(Q_n/Q_o)] - 1\}$ | $T_o\{[\exp(Q_n/Q_o)] - 1\}$ | $[60(1 - \chi_l)Q_c]/(\rho_o c_p V)$ |
| $D$ | $(D_m Qt)/[\chi_\alpha \Delta H_c A(H - z)]$ | $(D_m \alpha t^3)/[3\chi_\alpha \Delta H_c A(H - z)]$ | $(60 D_m Q)/(\chi_\alpha \Delta H_c V)$ |
| $Y_i$ | $(f_i Qt)/[\rho_o \chi_\alpha \Delta H_c A(H - z)]$ | $(f_i \alpha t^3)/[3\rho_o \chi_\alpha \Delta H_c A(H - z)]$ | $(60 f_i Q)/(\rho_o \chi_\alpha \Delta H_c V)$ |

where:
$A$ = horizontal cross-sectional area of space (ft$^2$)
$c_p$ = specific heat of ambient air (Btu/lb·°F)
$D = L^{-1} \log(I_o/I)$, optical density
$D_m\ DV/m_f$ = mass optical density (ft$^2$/lb) measured in a test stream containing all the smoke from a material test sample
$f_i$ = yield factor of species $i$ (lb species $i$/lb fuel)
$H$ = ceiling height (ft)
$\Delta H_c$ = heat of complete combustion (Btu/lb)
$Q$ = heat release rate of fire (Btu/sec)
$Q_c$ = convective portion of heat release rate (Btu/sec)
$Q_n = \int (1 - \chi_l)\ Q\ dt$
for steady fires: $Q_n = (1 - \chi_l) Qt$ (Btu)
for $t^2$ fires: $Q_n = (1 - \chi_l)\ \alpha t^3/3$ (Btu)
$Q_o = \rho_o c_p T_o A\ (H - z)$ (Btu)
$t$ = time from ignition (sec)
$T_o$ = absolute ambient temperature (°R)
$\Delta T$ = temperature rise in smoke layer (°F)
$V$ = volumetric venting rate (ft$^3$/min)
$Y_i$ = mass fraction of species $i$ (lb species $i$/lb of smoke)
$z$ = height from top of fuel to smoke layer interface (ft)
$\alpha$ = $t^2$ fire growth coefficient (Btu/sec$^3$)
$\rho_o$ = density of ambient air (lb/ft$^3$)
$\chi_\alpha$ = combustion efficiency factor, maximum value of 1 (Tewarson (1988))
$\chi_l$ = total heat loss factor from smoke layer to atrium boundaries, maximum value of 1, maximum temperature rise will occur if $\chi_l = 0$

**3.6.2 Height of First Indication of Smoke with No Smoke Exhaust Operating.**

**3.6.2.1 Steady Fires.** For steady fires, the height of the initial indications of smoke above the fire surface, $z$, can be estimated for any time, $t$, from Equation (3), where calculations yielding $z/H > 1.0$ mean that the smoke layer has not yet begun to descend.

$$\frac{z}{H} = 0.67 - 0.28 \ln\left(\frac{tQ^{1/3}/H^{4/3}}{A/H^2}\right) \quad (3)$$

where:

$z$ = height of the first indication of smoke above the fire surface (ft)
$H$ = ceiling height above the fire surface (ft)
$t$ = time (sec)
$Q$ = heat release rate from steady fire (Btu/sec)
$A$ = cross-sectional area of the space being filled with smoke (ft$^2$)

Equation (3) is based on experimental data from investigations using uniform cross-sectional areas with respect to height with $A/H^2$ ratios in the range from 0.9 to 14 and for values of $z/H^3 \geq 0.2$ [7, 10, 12, 13, 14]. This equation is for use with the worst-case condition, a fire away from any walls. The equation provides a conservative estimate of hazard because $z$ relates to the height where there is a first indication of smoke, rather than the smoke layer interface position.

**3.6.2.2* Unsteady Fires.** The descent of the height of the initial indications of smoke can also be estimated for certain types of unsteady fires, for example, $t$-squared fires. From basic theory and limited experimental evidence, the height of the initial indications of the smoke above the fire surface, $z$, can be estimated for a given time according to the following relation, where calculations yielding $z/H > 1.0$ mean that the smoke layer has not yet begun to descend:

$$\frac{z}{H} = 0.23\left(\frac{t}{t_g^{2/5} H^{4/5} (A/H^2)^{3/5}}\right)^{-1.45} \quad (4)$$

where:

$z$ = height of the first indication of smoke above the fire surface (ft)
$H$ = ceiling height above the fire surface (ft)
$t$ = time (sec)
$t_g$ = growth time (sec)

Equation (4) is based on experimental data from investigations with $A/H^2$ ratios in the range from 1.0 to 23 and for values of $z/H \geq 0.2$ [10]. Equation (4) is also based on uniform cross-sectional areas with respect to height. This equation is for use with the worst-case condition, a fire away from any walls. The equation also provides a conservative estimate of hazard because $z$ relates to the height at which there is a first indication of smoke, rather than the smoke layer interface position.

**3.6.2.3 Mass Consumption.** The equations presented in 3.6.2.1 and 3.6.2.2 are useful in evaluating the position of the layer at any time after ignition. For a steady fire, the total mass consumption required to sustain the steady heat release rate over the time period of interest can be determined as follows:

$$m = \frac{Q\Delta t}{H_c} \qquad (5)$$

where:

$m$ = total fuel mass consumed (lb)
$Q$ = heat release rate (Btu/sec)
$\Delta t$ = duration of fire (sec)
$H_c$ = heat of combustion of fuel (Btu/lb)

For a $t$-squared fire, the total mass consumed over the time period of interest can be determined as

$$m = \frac{333\Delta t^3}{H_c t_g^2} \qquad (6)$$

where:

$m$ = total fuel mass consumed (lb)
$\Delta t$ = duration of fire (sec)
$H_c$ = heat of combustion of fuel (Btu/lb)
$t_g$ = growth time (sec)

**3.6.2.4* Varying Cross-Sectional Geometries and Complex Geometries.** Equations (3) and (4) are based on experiments conducted in uniform cross-sectional areas. In practice, it is recognized that spaces being evaluated will not always exhibit a simple uniform geometry. The descent of the first indication of smoke in varying cross sections or complex geometric spaces can be affected by conditions such as sloped ceilings, variations in cross-sectional areas of the space, and projections into the rising plume. Where such irregularities occur, other methods of analysis should be considered. Other methods of analysis, which vary in their complexity but can be useful in dealing with complex and nonuniform geometries, are as follows:

(1) Scale models *(see 3.1.1.1 and 3.1.2)*
(2) CFD models *(see 3.1.1.3.2)*
(3)* Zone model adaptation
(4)* Bounding analysis

**3.7 Position of Smoke Layer Interface with Smoke Exhaust Operating.**

**3.7.1 Mass Rate of Smoke Exhaust Equals Mass Rate of Smoke Supplied.** After the smoke exhaust system has operated for a sufficient period of time, an equilibrium position of the smoke layer interface is achieved if the mass rate of smoke exhaust is equal to the mass rate of smoke supplied by the plume to the base of the smoke layer. Once achieved, this position should be maintained as long as the mass rates remain equal. See Section 3.8 for the mass rate of smoke supplied to the base of the smoke layer for different plume configurations.

**3.7.2 Mass Rate of Smoke Exhaust Not Equal to Mass Rate of Smoke Supplied.** With a greater rate of mass supply than exhaust, an equilibrium position of the smoke layer interface will not be achieved. The smoke layer interface can be expected to descend, but at a slower rate than if no exhaust were provided *(see 3.6.2)*. Table 3.7.2 includes information on the smoke layer position as a function of time for axisymmetric plumes of steady fires, given the inequality of the mass rates. For other plume configurations, a computer analysis is required.

**Table 3.7.2 Increase in Time for Smoke Layer Interface to Reach Selected Position**

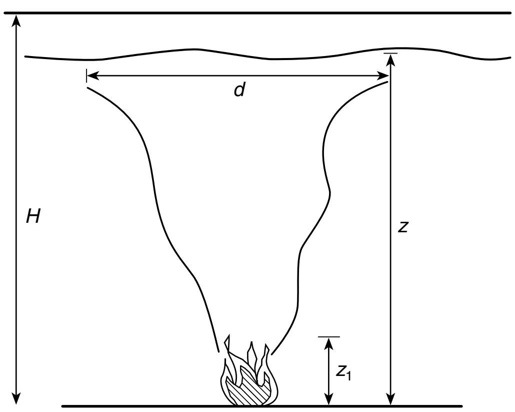
| | | $t/t_o$ | | | | | |
|---|---|---|---|---|---|---|---|
| **$z/H$** | **$m/m_e$ =** | **0.25** | **0.35** | **0.5** | **0.7** | **0.85** | **0.95** |
| 0.2 | | 1.12 | 1.19 | 1.3 | 1.55 | 1.89 | 2.49 |
| 0.3 | | 1.14 | 1.21 | 1.35 | 1.63 | 2.05 | 2.78 |
| 0.4 | | 1.16 | 1.24 | 1.4 | 1.72 | 2.24 | 3.15 |
| 0.5 | | 1.17 | 1.28 | 1.45 | 1.84 | 2.48 | 3.57 |
| 0.6 | | 1.20 | 1.32 | 1.52 | 2.00 | 2.78 | 4.11 |
| 0.7 | | 1.23 | 1.36 | 1.61 | 2.20 | 3.17 | 4.98 |
| 0.8 | | 1.26 | 1.41 | 1.71 | 2.46 | 3.71 | 6.25 |

where:
$z$ = design height of smoke layer interface above fire source
$H$ = ceiling height above fire source
$t$ = time for smoke layer interface to descend to $z$
$t_o$ = value of $t$ in absence of smoke exhaust *[see Equation (3)]*
$m$ = mass flow rate of smoke exhaust (minus any mass flow rate into smoke layer from sources other than the plume)
$m_e$ = value of $m$ required to maintain smoke layer interface indefinitely at $z$ *[see Equation (8)]*

**3.8 Rate of Smoke Mass Production.** The height of the smoke layer interface can be maintained at a constant level by exhausting the same mass flow rate from the layer as is supplied by the plume. The rate of mass supplied by the plume depends on the configuration of the smoke plume. Three smoke plume configurations are addressed in this guide. The exhaust fan inlets should be sized and distributed in the space to be exhausted to minimize the likelihood of air beneath the smoke layer from being drawn through the layer, a phenomenon sometimes referred to as plugholing. To accomplish this, the velocity of the exhaust inlet should not exceed a value to cause fresh air to be drawn into the smoke layer.

**3.8.1 Axisymmetric Plumes.** An axisymmetric plume *(see Figure 3.8.1)* is expected for a fire originating on the atrium floor, removed from any walls. In this case, air is entrained from all sides and along the entire height of the plume until the plume becomes submerged in the smoke layer.

**FIGURE 3.8.1 Axisymmetric plume.**




**3.8.1.1** The mass rate of smoke production can be estimated, based on the rate of entrained air, because the mass rate of combustion products generated from the fire is generally much less than the rate of air entrained in the plume.

**3.8.1.2*** Several entrainment relations for axisymmetric fire plumes have been proposed. Those recommended herein were those first derived in conjunction with the 1982 edition of NFPA 204, *Guide for Smoke and Heat Venting*. These relations were later slightly improved by the incorporation of a virtual origin and were also compared against other entrainment relations (see NFPA 204, *Guide for Smoke and Heat Venting*, and Heskestad (1982)).

The following entrainment relations are essentially those presented in NFPA 204, *Guide for Smoke and Heat Venting*. Effects of virtual origin are ignored, because they would generally be small in the present application and thus far can only be adequately predicted for pool fires. The definition of a limiting elevation, corresponding approximately to the luminous flame height, is given as

$$z_l = 0.533 Q_c^{2/5} \qquad (7)$$

where:

$z_l$ = limiting elevation (ft)

$Q_c$ = convective portion of heat release rate (Btu/sec)

The plume mass flow rate, *m*, above the limiting elevation is predicted from

$$m = [0.022 Q_c^{1/3} z^{5/3}] + 0.0042 Q_c \quad (z > z_l) \qquad (8)$$

where:

$m$ = mass flow rate in plume at height $z$ (lb/sec)

$z$ = height above the fuel (ft)

The plume mass flow rate below the flame tip is predicted from

$$m = 0.0208 Q_c^{3/5} z \quad (z \le z_l) \qquad (9)$$

**3.8.1.3** The rate of mass supplied by the plume to the smoke layer is obtained from Equation (9) for clear heights less than the flame height *[see Equation (7)]* and otherwise from Equation (8). The clear height is selected as the design height of the smoke layer interface above the fire source.

**3.8.1.4** It should be noted that Equations (8) and (9) do not explicitly address the types of materials involved in the fire, other than through the rate of heat release. This is due to the mass rate of air entrained being much greater than the mass rate of combustion products generated and to the amount of air entrained only being a function of the strength — that is, rate of heat release of the fire.

**3.8.1.5** Fires can be located near the edge or a corner of the open space. In this case, entrainment might not be from all sides of the plume, resulting in a lesser smoke production rate than where entrainment can occur from all sides. Thus, conservative design calculations should be conducted based on the assumption that entrainment occurs from all sides.

**3.8.2 Balcony Spill Plumes.**

**3.8.2.1*** A balcony spill plume is one that flows under and around a balcony before rising, giving the impression of spilling from the balcony, from an inverted perspective *(see Figure 3.8.2.1)*. Scenarios with balcony spill plumes involve smoke rising above a fire, reaching a ceiling, balcony, or other significant horizontal projection, then traveling horizontally toward the edge of the "balcony." Characteristics of the resulting balcony spill plume depend on characteristics of the fire, width of the spill plume, and height of the ceiling above the fire. In addition, the path of horizontal travel from the plume centerline to the balcony edge is significant.

For situations involving a fire in a communicating space immediately adjacent to the atrium, air entrainment into balcony spill plumes can be calculated from Equation (10):

$$m = 0.12(QW^2)^{1/3}(z_b + 0.25H) \qquad (10)$$

where:

$m$ = mass flow rate in plume (lb/sec)

$Q$ = heat release rate of the fire (Btu/sec)

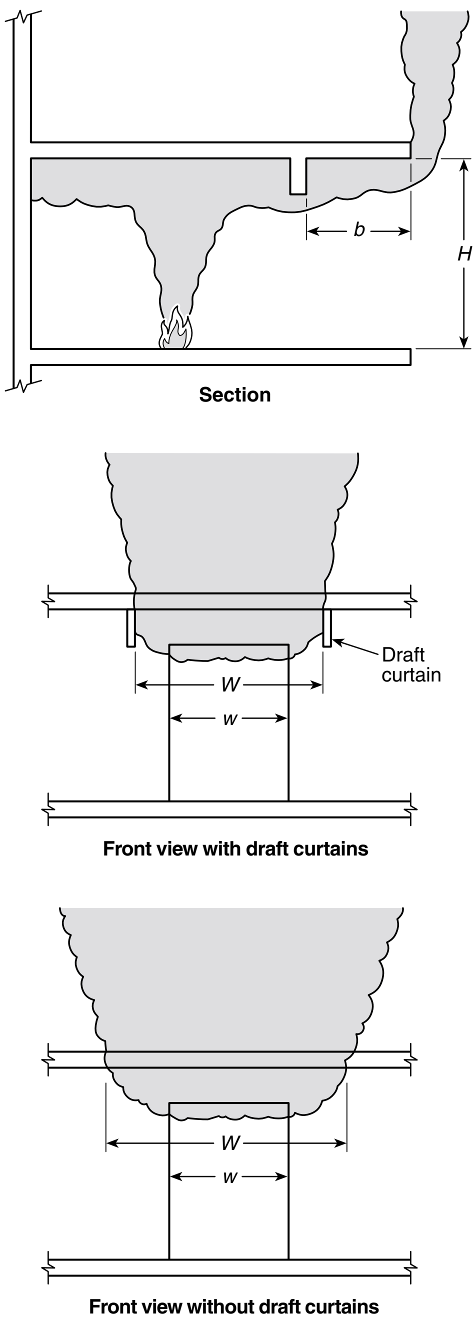
$W$ = width of the plume as it spills under the balcony (ft)

$z_b$ = height above the balcony (ft)

$H$ = height of balcony above fuel (ft)

Equation (10) is based on Law's interpretation [16] of small-scale experiments by Morgan and Marshall [17]. Equation (10) should be regarded as an approximation to a complicated problem.

**FIGURE 3.8.2.1 Balcony spill plume.**




**3.8.2.2** When $z_b$ is approximately 13 times the width, the balcony spill plume is expected to have the same production rate as an axisymmetric plume. Consequently, for $z_b > 13W$, the smoke production rate from a balcony spill plume should be estimated using Equation (8).

**3.8.2.3** The width of the plume, $W$, can be estimated by considering the presence of any physical barriers protruding below the balcony to restrict horizontal smoke migration under the balcony. In the absence of any barriers, visual observations of the width of the balcony spill plume at the balcony edge were made in a set of small-scale experiments by Morgan and Marshall [17] and analyzed by Law [16]. In these experiments, the fire was in a communicating space, immediately adjacent to the atrium. An equivalent width can be defined by equating the entrainment from an unconfined balcony spill plume to that from a confined balcony spill plume. The equivalent width is evaluated using the following expression:

$$W = w + b \tag{11}$$

where:

$W$ = the width of the plume (ft)

$w$ = the width of the opening from the area of origin (ft)

$b$ = the distance from the opening to the balcony edge (ft)

### 3.8.3 Window Plumes.

**3.8.3.1** Plumes issuing from wall openings, such as doors and windows, into a large-volume, open space are referred to as window plumes *(see Figure 3.8.3.1)*. After room flashover, the total heat release rate can be expected to be governed by the airflow rate through the wall opening from the open space; that is, the fire is "ventilation controlled." The heat release rate can be related to the characteristics of the ventilation opening. Based on experimental data for wood and polyurethane, the average heat release rate is given as (Modak and Alpert (1978) and Tewarson (1988).

$$Q = 61.2 A_w H_w^{1/2} \tag{12}$$

where:

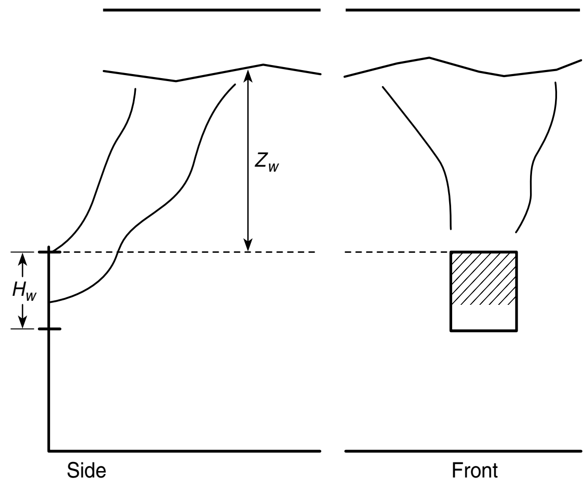
$Q$ = heat release rate (Btu/sec)

$A_w$ = area of ventilation opening (ft$^2$)

$H_w$ = height of ventilation opening (ft)

This assumes that the heat release is limited by the air supply to the compartment, the fuel generation is limited by the air supply, and excess fuel burns outside the compartment using air entrained outside the compartment. The methods in this section are also valid only for compartments having a single ventilation opening.

**FIGURE 3.8.3.1 Window plume.**




**3.8.3.2** The air entrained into the window plume can be determined by analogy with the axisymmetric plume. This is accomplished by determining the entrainment rate at the tip of the flames issuing from the window and determining the height in an axisymmetric plume that would yield the same amount of entrainment. As a result of this analogy, a correction factor addressing the difference between the actual flame height and the equivalent axisymmetric plume height can be applied to the axisymmetric plume equation according to the following relation:

$$a = [2.40 A_w^{2/5} H_w^{1/5}] - 2.1 H_w \quad (13)$$

where:
$a$ = effective height (ft)
$A_w$ = area of ventilation opening (ft$^2$)
$H_w$ = height of ventilation opening (ft)

Then, the mass entrainment for window plumes is given as

$$m = [0.022\, Q_c^{1/3} (z_w + a)^{5/3}] + 0.0042\, Q_c \quad (14)$$

where $z_w$ = height above the top of the window (ft).

Substituting for $Q_c$ from Equation (12),

$$m = [0.077 (A_w H_w^{1/2})^{1/3} (z_w + a)^{5/3}] + 0.18 A_w H_w^{1/2} \quad (15)$$

The virtual source height is determined as the height of a fire source in the open that gives the same entrainments as the window plume at the window plume flame tip. Further entrainment above the flame tip is assumed to be the same as for a fire in the open. Although this development is a reasonably formulated model for window plume entrainment, no data are available to validate its use. As such, the accuracy of the model is unknown.

**3.8.4 Plume Width.** As a plume rises, it entrains air and widens. Generally the total plume diameter can be estimated as

$$d = K_d z \quad (16)$$

where:
$d$ = plume diameter (ft)
$z$ = height (ft)
$K_d$ = diameter constant

The diameter constant can range from 0.25 to 0.5. It is recommended that values of $K_d$ be chosen so that the resulting calculations are conservative:

(1) $K_d$ = 0.5 results in a conservative estimate of plume contact with walls.
(2) $K_d$ = 0.25 results in conservative estimates when considering beam detection of the smoke plume.

**3.8.5 Plume Temperature.**

**3.8.5.1 Average Temperature.** Based on the first law of thermodynamics, the average temperature of the plume is

$$T_p = T_o + \frac{Q_c}{m C_p} \quad (17)$$

where:
$T_p$ = average plume temperature at elevation $z$ (°F)
$T_o$ = ambient temperature (°F)
$Q_c$ = convective portion of heat release (Btu/sec)
$C_p$ = specific heat of plume gases (0.24 Btu/lb-°F)
$m$ = mass flow rate of the plume (lb/sec)

The mass flow rate of the plume can be calculated from Equation (8) or (9). Equation (8) was developed for strongly buoyant plumes; for small temperature differences between the plume and ambient, errors due to low buoyancy could be significant. This topic needs further study; in the absence of better data, it is recommended that the plume equations not be used when this temperature difference is small (<4°F).

**3.8.5.2 Centerline Temperature.** The temperature from Equation (17) is a mass flow average, but the temperature varies over the plume cross section. The plume temperature is greatest at the centerline of the plume; the centerline temperature is of interest when atria are tested by real fires, as discussed later. The centerline temperature can be approximated from

$$T_{cp} = T_a + 9.1 \left( \frac{T_a}{g C_p^2 \rho_a^2} \right)^{1/3} \frac{Q^{2/3}}{z^{5/3}} \quad (18)$$

where:
$T_{cp}$ = absolute centerline plume temperature at elevation $z$ (°R)
$T_a$ = absolute ambient temperature (°R)
$\rho_a$ = density of ambient air (lb/ft$^3$)
$g$ = acceleration of gravity (32.2 ft/sec$^2$)
$z$ = height above top of fuel (ft)
$C_p$ = specific heat of air (0.241 Btu/lb-°F)
$Q$ = heat release rate of the fire (Btu/sec)

**3.9* Number of Exhaust Inlets.** When the smoke layer depth below an exhaust inlet is relatively shallow, a high exhaust rate can lead to entrainment of cold air from the clear layer. This phenomenon is called plugholing. The number of exhaust inlets needs to be chosen so the maximum flow rates for exhaust without plugholing are not exceeded. Accordingly, more than one exhaust inlet might be needed. The maximum mass flow rate, which can be efficiently extracted using a single exhaust inlet, is given as (CIBSE (1995))

$$m_{\max} = 0.354\beta d^{5/2}\left[\frac{T_s - T_o}{T_s}\right]^{1/2}\left[\frac{T_o}{T_s}\right]^{1/2} \quad (19)$$

where:

$m_{\max}$ = maximum mass rate of exhaust without plugholing (lb/sec)

$T_s$ = absolute temperature of the smoke layer (°R)

$T_o$ = absolute ambient temperature (°R)

$d$ = depth of smoke layer below exhaust inlet (ft)

$\beta$ = exhaust location factor (dimensionless)

Based on limited information, suggested values of $\beta$ are 2.0 for a ceiling exhaust inlet near a wall, 2.0 for a wall exhaust inlet near the ceiling, and 2.8 for a ceiling exhaust inlet far from any walls. It is suggested that $d/D$ be greater than 2, where $D$ is the diameter of the inlet. For rectangular exhaust inlets, $D = 2ab/(a + b)$, where $a$ and $b$ are the length and width of the inlet.

The maximum volumetric flow rate that can be extracted through an exhaust inlet is given as

$$V_{\max} = 0.537\beta d^{5/2}[T_o(T_s - T_o)]^{1/2} \quad (20)$$

where $V_{\max}$ = maximum volumetric flow rate at $T_s$ (ft$^3$/min).

When the exhaust at an inlet is near this maximum flow rate, adequate separation between exhaust inlets needs to be maintained to minimize interaction between the flows near the inlets. One criterion for the separation between inlets is that it be at least the distance from a single inlet that would result in arbitrarily small velocity based on sink flow. Using 40 ft/min as the arbitrary velocity, the minimum separation distance for inlets located in a wall near the ceiling (or in the ceiling near the wall) is

$$S_{\min} = 0.023\beta V_e^{1/2} \quad (21)$$

where:

$S_{\min}$ = minimum edge-to-edge separation between inlets (ft)

$V_e$ = volumetric flow rate (ft$^3$/min)

$\beta$ = exhaust location factor (dimensionless)

**3.10 Minimum Smoke Layer Depth.** The smoke layer must be deep enough to include the ceiling smoke jet as described in 2.3.1.

**3.11* Volumetric Flow Rate.** For practical reasons, expressing the smoke production rate in terms of a volumetric rate (ft$^3$/min) might be preferred over a mass rate. This preference can be accommodated by dividing the mass flow rate by the density of smoke:

$$V = 60\ m/\rho \quad (22)$$

where $\rho$ = density of smoke (lb/ft$^3$).

The volumetric flow rate determined using Equation (22) is at the smoke layer temperature. For a smoke management system designed to operate under equilibrium conditions *(see 3.7.1)*, the smoke exhaust system should be designed to provide sufficient volumetric exhaust capacity at the temperature of the smoke layer.

**3.12 Maximum Air Supply Velocity.** The supply velocity of the makeup air at the perimeter of the large, open space needs to be limited to sufficiently low values so as not to deflect the fire plume significantly, which would increase the air entrainment rate, or disturb the smoke interface. A maximum makeup supply velocity of about 200 ft/min is recommended, based on flame deflection data (Mudan and Croce (1988). Where maintaining a smoke layer height is not a design goal, plume disruption due to supply velocity might not be detrimental.

**3.13 Opposed Airflow Requirements.**

**3.13.1** To prevent smoke originating in a communicating space from propagating into the large space, the communicating space must be exhausted at a sufficient rate to cause the average air velocity in the opening from the large space to exceed a lower limit. The limiting average velocity, $v$, can be calculated from Heskestad (1989).

$$v = 38[gH(T_f - T_o)/(T_f + 460)]^{1/2} \quad (23)$$

where:

$v$ = air velocity (ft/min)

$g$ = acceleration of gravity (32.2 ft/sec$^2$)

$H$ = height of the opening (ft)

$T_f$ = temperature of heated smoke (°F)

$T_o$ = temperature of ambient air (°F)

For example, with $H$ = 10 ft, $T_f$ = 165°F (considered realistic for sprinklered spaces), and $T_o$ = 70°F, the limiting velocity becomes 270 ft/min. For the same conditions with $T_f$ = 1640°F (considered realistic for unsprinklered spaces), the limiting velocity becomes 594 ft/min.

**3.13.2** To prevent smoke originating in the large-volume space from propagating into the communicating space, air must be supplied from the communicating space at a sufficient rate to cause the average air velocity in the opening to the large space to exceed a lower limit [i.e., the limiting average velocity ($v_e$) in Equation (24)]. Two cases can be differentiated. In one case, the opening to the communicating space is located below the position of the smoke layer interface, and the communicating space is exposed to smoke from a plume located near the perimeter of the open space, in which case the limiting average velocity, $v_e$, can be estimated from

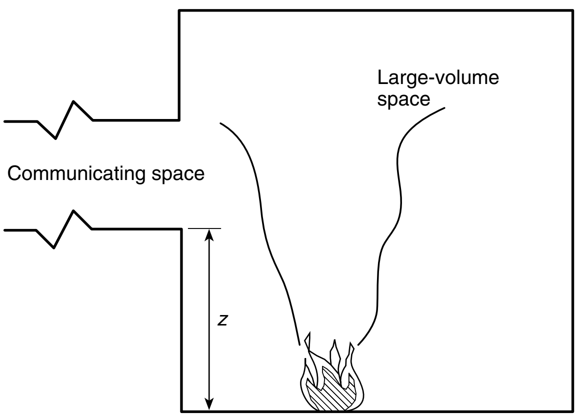
$$v_e = 17[Q/z]^{1/3} \qquad (24)$$

where:

$v_e$ = limiting average velocity (ft/min)
$Q$ = heat release rate of the fire (Btu/sec)
$z$ = distance above the base of the fire to the bottom of the opening (ft) *(see Figure 3.13.2)*

The limiting average velocity ($v_e$) should not exceed 200 ft/min. This equation should not be used when $z < 10$ ft. In the other case, the opening to the communicating space is located above the position of the smoke layer interface, in which case Equation (24) is used to calculate the limiting average velocity (setting $v = v_e$), where $T_f - T_o$ is the value of $\Delta T$ from Table 3.5 and $T_f = \Delta T + T_o$.

**FIGURE 3.13.2 Measurement of distance above base of fire to bottom of opening.**




## Chapter 4 Equipment and Controls

### 4.1 General.

**4.1.1** The dynamics, buoyancy, plume, and stratification of the potential fire, together with the width and height of the large-volume space, must all be considered when selecting the smoke management system. Generally, the HVAC systems designed for these spaces do not have the capacity for use as a smoke management system, nor are the supply and exhaust air grilles located for their proper use in such a system. In most cases, therefore, a dedicated smoke management system should be considered.

**4.1.2** Some existing large-volume spaces that have glass walls or skylights have been reported to experience temperatures up to 200°F (93°C) because of solar loads. Any building materials located in such areas need to be capable of operating in this heated environment.

**4.2 Exhaust Fans.** Exhaust fans should be selected to operate at the design conditions of the smoke and fire. Although dilution with ambient air might significantly cool down the fire temperature, in some instances the direct effects of the fire are on the equipment.

**4.3 Makeup Air System.** The simplest method of introducing makeup air into the space is through direct openings to the outside such as through doors and louvers, which can be opened upon system activation. Such openings can be coordinated with the architectural design and be located as required below the design smoke layer. For locations where such openings are impractical, a mechanical supply system can be considered. This system could possibly be an adaptation of the building's HVAC system if capacities, outlet grille locations, and velocities are suitable. For such systems, means should be provided to prevent supply systems from operating until exhaust flow has been established to avoid pressurization of the fire area. For those locations where climates are such that the damage to the space or contents could be extensive during testing or frequent inadvertent operation of the system, consideration should be given to heating the makeup air.

### 4.4 Control Systems.

**4.4.1 Simplicity.** Simplicity should be the goal of each smoke management control system. Complex systems should be avoided. Such systems tend to confuse, might not be installed correctly, might not be properly tested, might have a low level of reliability, and might never be maintained.

**4.4.2 Coordination.** The control system should fully coordinate the smoke management system interlocks and interface with the fire protection signaling system, sprinkler system, HVAC system, and any other related systems.

**4.4.3 HVAC System Controls.** Operating controls for the HVAC system should accommodate the smoke management mode, which must have the highest priority over all other control modes.

**4.4.4 Response Time.** The smoke management system activation should be initiated immediately after receipt of an appropriate activation command. The smoke management system should activate individual components, such as dampers and fans, in sequence as necessary to avoid physical damage to the equipment. Careful consideration should also be given to stopping operating equipment in proper sequence, since some fans take a long time to wind down and the closing of dampers against airflow can cause serious damage. The total response time, including that necessary for detection, shutdown of operating equipment, and smoke management system start-up, should allow for full operational mode to be achieved before the conditions in the space exceed the design smoke conditions.

**4.4.5* Control System Verification and Instrumentation.** Every system should have means of ensuring it will operate if activated. The means and frequency vary according to the complexity and importance of the system.

**4.4.6 Manual Control.** Manual control of all systems should be provided at a centralized location. Such controls should be able to override any interlocking features built into the automatically operated system. *(See NFPA 92A, Recommended Practice for Smoke-Control Systems, for devices that should not be overridden.)*

### 4.5 Electrical Services.

**4.5.1** Electrical installations should meet the requirements of NFPA 70, *National Electrical Code.*

**4.5.2** Normal electrical power serving air-conditioning systems generally has sufficient reliability for nondedicated zoned smoke-control systems.

4.5.3 Whether or not standby power is needed should be considered for smoke-control systems and their control systems.

**4.6 Materials.**

**4.6.1** Materials used for systems providing smoke control should conform to NFPA 90A, *Standard for the Installation of Air-Conditioning and Ventilating Systems*, and other applicable NFPA documents.

**4.6.2** Duct materials should be selected and ducts designed to convey smoke, to withstand additional pressure (both positive and negative) by the supply and exhaust fans when operating in a smoke-control mode, and to maintain their structural integrity during the period for which the system should operate.

**4.6.3** Equipment, including, but not limited to, fans, ducts, and balance dampers, should be suitable for its intended use and the probable temperatures to which it might be exposed.

**4.7 Other Building HVAC Systems.** If other systems in the building are used as part of the smoke management system serving the large-volume area, NFPA 92A, *Recommended Practice for Smoke-Control Systems*, should be referred to for guidance.

## Chapter 5 Testing

**5.1 General.**

**5.1.1** This chapter provides recommendations for the testing of smoke management systems. Each system should be tested against its specific design criteria. The test procedures described herein are divided into the following three categories:

(1) Component system testing
(2) Acceptance testing
(3) Periodic testing and maintenance

**5.1.2** It is recommended that the building owner, designer, and authority having jurisdiction meet during the planning stage of the project to share their thoughts and objectives concerning the smoke management system contemplated and agree on the design criteria and the pass/fail performance tests for the systems. Such an agreement helps to overcome the numerous problems that occur during final acceptance testing and facilitates obtaining the certificate of occupancy.

**5.1.3** Contract documents should include all acceptance testing procedures so that all parties have a clear understanding of the system objectives, testing procedures, and pass/fail criteria.

**5.2 Component System Testing.**

**5.2.1** The intent of component system testing is to establish that the final installation complies with the specified design, is functioning properly, and is ready for acceptance testing. Responsibility for testing should be defined clearly prior to component system testing.

**5.2.2** Prior to testing, the party responsible for this testing should verify completeness of building construction, including the following architectural features:

(1) Integrity of any partition, floor, or other member intended to resist smoke passage
(2) Firestopping
(3) Doors and closers related to smoke control
(4) Glazing that encloses a large-volume space

**5.2.3** The operational testing of each individual system component should be performed as it is completed during construction. These operational tests will normally be performed by various trades before interconnection is made to integrate the overall smoke management system. It should be documented in writing that each individual system component's installation is complete and the component is functional. Each component test, including such items as speed, volume, sensitivity calibration, voltage, and amperage, should be individually documented.

**5.2.4** Testing should include the following subsystems to the extent that they affect or are affected by the operation of the smoke management system:

(1) Fire alarm system *(see NFPA 72, National Fire Alarm Code)*
(2) Energy management system
(3) Building management system
(4) Heating, ventilating, and air-conditioning (HVAC) equipment
(5) Electrical equipment
(6) Temperature control system
(7) Power sources
(8) Standby power
(9) Automatic suppression systems
(10) Automatic operating doors and closures
(11) Other smoke-control systems
(12) Emergency elevator operation

**5.3 Acceptance Testing.**

**5.3.1 General.** The intent of acceptance testing is to demonstrate that the final integrated system installation complies with the specific design and is functioning properly. Representatives of one or more of the following should be present to grant acceptance:

(1) Authority having jurisdiction
(2) Owner
(3) Designer

All documentation from component system testing should be available for inspection.

**5.3.2 Test Parameters.** The following parameters need to be measured during acceptance testing:

(1) Total volumetric flow rate
(2) Airflow velocities
(3) Airflow direction
(4) Door-opening forces
(5) Pressure differentials
(6) Ambient temperature

**5.3.3 Test Equipment.** The following equipment might be needed to perform acceptance testing:

(1) Differential pressure gauges, inclined water manometers, or electronic manometer [instrument ranges 0–0.25 in. w.g. (0–62.5 Pa) and 0–0.50 in. w.g. (0–125 Pa) with 50 ft (15.2 m) of tubing]
(2) Scale suitable for measuring door-opening force
(3) Anemometer, including traversing equipment
(4) Ammeter
(5) Door wedges
(6) Tissue paper roll or other convenient device for indicating direction of airflow

(7) Signs indicating that a test of the smoke management system is in progress and that doors should not be opened
(8) Several walkie-talkie radios (They have been found to be useful to help coordinate equipment operation and data recording.)

**5.3.4 Testing Procedures.** The acceptance testing should consider inclusion of the procedures described in 5.3.4.1 through 5.3.4.6.

**5.3.4.1** Prior to beginning acceptance testing, all building equipment should be placed in the normal operating mode, including equipment that is not used to implement smoke management, such as toilet exhaust, elevator shaft vents, elevator machine room fans, and similar systems.

**5.3.4.2** Wind speed, direction, and outside temperature should be recorded for each test day. If conditions change greatly during the testing, new conditions should be recorded.

**5.3.4.3** If standby power has been provided for the operation of the smoke management system, the acceptance testing should be conducted while on both normal and standby power. Disconnect the normal building power at the main service disconnect to simulate true operating conditions in this mode.

**5.3.4.4** The acceptance testing should include demonstrating that the correct outputs are produced for a given input for each control sequence specified. Consideration should be given to the following control sequences so that the complete smoke management sequence is demonstrated:

(1) Normal mode
(2) Automatic smoke management mode for first alarm
(3) Manual override of normal and automatic smoke management modes
(4) Return to normal

**5.3.4.5** It is acceptable to perform acceptance tests for the fire protective signaling system in conjunction with the smoke management system. One or more device circuits on the fire protective signaling system can initiate a single input signal to the smoke management system. Therefore, consideration should be given to establishing the appropriate number of initiating devices and initiating device circuits to be operated to demonstrate the smoke management system operation.

**5.3.4.6** Much can be accomplished to demonstrate smoke management system operation without resorting to demonstrations that use smoke or products that simulate smoke.

**5.3.5 Large-Volume Space Smoke Management Systems.**

**5.3.5.1** The large-volume space can come in many configurations, each with its own peculiarities. They can be tall and thin or short and wide; have balconies and interconnecting floors; be open or closed to adjacent floors; have corridors and stairs for use in evacuation or have only exposed walls and windows (sterile tube); and be a portion of a hotel, hospital, shopping center, or arena. Specific smoke management criteria must be developed for each unique situation.

**5.3.5.2** Verify the exact location of the perimeter of each large-volume space smoke management system, identify any door openings into that space, and identify all adjacent areas that are to remain open and that are to be protected by airflow alone. For larger openings, the velocity must be measured by making appropriate traverses of the opening.

**5.3.5.3** With the HVAC systems in their normal mode, measure pressure differences across all door barriers and airflow velocities at interfaces with open areas. Using the scale, measure the force necessary to open each door.

**5.3.5.4** Activate the smoke management system. Verify and record the operation of all fans, dampers, doors, and related equipment. Measure fan exhaust capacities and air velocities through inlet doors and grilles or at supply grilles if there is a mechanical makeup air system. Measure the force to open exit doors.

**5.3.5.5** Measure and record the pressure difference across all doors that separate the smoke management system area from adjacent spaces and the velocities at interfaces with open areas.

**5.3.6 Other Test Methods.**

**5.3.6.1** The test methods previously described should provide an adequate means to evaluate the smoke management system's performance. Other test methods have been used historically in instances where the authority having jurisdiction requires additional testing. These test methods have limited value in evaluating certain system performance, and their validity as a method of testing a smoke management system is questionable.

**5.3.6.2*** As covered in the preceding chapters, the dynamics of the fire plume, buoyancy forces, and stratification are all major critical elements in the design of the smoke management system. Therefore, to test the system properly, a real fire condition would be the most appropriate and meaningful test. However, there are many valid reasons why such a fire is usually not practical in a completed building. Open flame/actual fire testing might be dangerous and should not normally be attempted. Any other test is a compromise. If a test of the smoke management system for building acceptance is mandated by the authority having jurisdiction, such a test condition would become the basis of design and might not in any way simulate any real fire condition. More importantly, it could be a deception and provide a false sense of security that the smoke management system would perform adequately in a real fire emergency.

Smoke bomb tests do *not* provide the heat, buoyancy, and entrainment of a real fire and are *not* useful in evaluating the real performance of the system. A system designed in accordance with this document and capable of providing the intended smoke management might not pass smoke bomb tests. Conversely, it is possible for a system that is incapable of providing the intended smoke management to pass smoke bomb tests. Because of the impracticality of conducting real fire tests, the acceptance tests described in this document are directed to those aspects of smoke management systems that can be verified.

**5.3.7 Testing Documentation.** Upon completion of acceptance testing, a copy of all operational testing documentation should be provided to the owner. This documentation should be available for reference for periodic testing and maintenance.

**5.3.8 Owner's Manuals and Instruction.** Information should be provided to the owner that defines the operation and maintenance of the system. Basic instruction on the operation of the system should be provided to the owner's representatives. Because the owner might assume beneficial use of the smoke management system wherever there is completion of acceptance testing, this basic instruction should be completed prior to acceptance testing.

**5.3.9 Partial Occupancy.** Acceptance testing should be performed as a single step when obtaining a certificate of occupancy. However, if the building is to be completed or occupied in stages, acceptance tests of the entire system should be conducted in order to obtain temporary certificates of occupancy.

**5.3.10 Modifications.** All operation and acceptance tests should be performed on the applicable part of the system wherever there are system changes and modifications. Documentation should be updated to reflect these changes or modifications.

**5.4 Periodic Testing.**

**5.4.1** During the life of the building, maintenance is essential to ensure that the smoke management system will perform its intended function under fire conditions. Proper maintenance of the system should, as a minimum, include the periodic testing of all equipment, such as initiating devices, fans, dampers, controls, doors, and windows. The equipment should be maintained in accordance with the manufacturer's recommendations. *(See NFPA 90A, Standard for the Installation of Air-Conditioning and Ventilating Systems, for suggested maintenance practices.)*

**5.4.2** The periodic tests should determine that the installed systems will continue to operate in accordance with the approved design. It is preferable to include in the tests both the measurements of airflow quantities and the pressure differentials at the following locations:

(1) Across smoke barrier openings
(2) At the air makeup supplies
(3) At smoke exhaust equipment

All data points should coincide with the acceptance test location to facilitate comparison measurements.

**5.4.3** The system should be tested at least semiannually by persons who are thoroughly knowledgeable in the operation, testing, and maintenance of the systems. The results of the tests should be documented in the operations and maintenance log and made available for inspection. The smoke management system should be operated for each sequence in the current design criteria. The operation of the correct outputs for each given input should be observed. Tests, if applicable, should also be conducted under standby power.

**5.4.4** Special arrangements might have to be made for the introduction of large quantities of outside air into occupied areas or computer centers when outside temperature and humidity conditions are extreme and when such unconditioned air might damage contents. Since smoke management systems can override limit controls such as freezestats, tests should be conducted when outside air conditions will not cause damage to equipment and systems.

## Chapter 6 Referenced Publications

**6.1** The following documents or portions thereof are referenced within this guide and should be considered as part of its recommendations. The edition indicated for each referenced document is the current edition as of the date of the NFPA issuance of this guide. Some of these documents might also be referenced in this guide for specific informational purposes and, therefore, are also listed in Appendix F.

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

NFPA 70, *National Electrical Code®*, 1999 edition.
NFPA 72, *National Fire Alarm Code®*, 1999 edition.
NFPA 90A, *Standard for the Installation of Air-Conditioning and Ventilating Systems*, 1999 edition.
NFPA 92A, *Recommended Practice for Smoke-Control Systems*, 2000 edition.
NFPA *101®*, *Life Safety Code®*, 2000 edition.
NFPA 204, *Guide for Smoke and Heat Venting*, 1998 edition.

**6.1.2 Other Publications.**

**6.1.2.1 UL Publications.** Underwriters Laboratories Inc., 333 Pfingsten Road, Northbrook, IL 60062.

UL 555, *Standard for Safety Fire Dampers*, 1999.
UL 555S, *Standard for Safety Leakage Rated Dampers for Use in Smoke Control Systems*, 1999.

**6.1.3 Additional Publications.**

Babrauskas, V., and Krasny, J., *Fire Behavior of Upholstered Furniture*, NBS Monograph 173, National Bureau of Standards (now National Institute of Standards and Technology), November 1985.

Beyler, C., "Fire Plumes and Ceiling Jets," *Fire Safety Journal*, 11, pp. 63–65, 1986.

CIBSE, *Relationships for Smoke Control Calculations*, TM 19, Chartered Institution of Building Services Engineers, London, 1995.

Heskestad, G., *Engineering Relations for Fire Plumes*, SFPE TR 82-8, Boston, Society for Fire Protection Engineers, 1982.

Heskestad, G., *Inflow Air Required at Wall and Ceiling Apertures to Prevent Escape of Fire Smoke*, FMRC J.I 0Q4E4.RU, Factory Mutual Research Corporation, July 1989.

Law, M., "A Note on Smoke Plumes from Fires in Multilevel Shopping Malls," *Fire Safety Journal* 10, p. 197, 1986.

Milke, J., and Klote, J., "Smoke Management in Large Spaces in Buildings," Building Control Commission, Melbourne, Australia, July 1998.

Modak, A. T., and Alpert, R. L., *Influence on Fire Growth — Volume I: Guide to Test Data*, FMRC 0A0R2.BU-8, Factory Mutual Research, Norwood, MA, 1978.

Morgan, H. P., and Marshall, N. R., *Smoke Control Measures in Covered Two-Story Shopping Malls Having Balconies and Pedestrian Walkways*, BRE CP 11/79, Borehamwood, 1979.

Morton, B. R., Taylor, Sir Geoffrey, and Turner, J. S., "Turbulent Gravitational Convection from Maintained and Instantaneous Sources," *Proc. Royal Society A* 234, 1–23, 1956.

Mudan, K. S., and Croce, P. A., "Fire Hazard Calculations for Large Open Hydrocarbon Fires," *SFPE Handbook of Fire Protection Engineering*, National Fire Protection Association, Quincy, MA, 1988.

Nelson, H. E., and MacLennan, H. A., "Emergency Movement," *SFPE Handbook of Fire Protection Engineering*, 2nd ed., P. J. DiNenno (ed.), National Fire Protection Association, Quincy, MA, 1995.

Pauls, J., "Movement of People," *SFPE Handbook of Fire Protection Engineering*, 2nd ed., P. J. DiNenno (ed.), National Fire Protection Association, Quincy, MA, 1995.

Schifiliti, R. P., and Pucci, W. E., "Fire Detection Modeling, State of the Art," Fire Detection Institute, Bloomfield, CT, May 6, 1996.

Tewarson, A., "Generation of Heat and Chemical Compounds," *SFPE Handbook of Fire Protection Engineering*, National Fire Protection Association, Quincy, MA, 1988.

## Appendix A Explanatory Material

**A.1.2** This guide makes no differentiation in the technical approach to smoke management in atria and that in covered malls.

**A.1.4.2 Ceiling Jet.** Normally, the temperature of the ceiling jet is greater than the adjacent smoke layer.

**A.1.4.3 Communicating Space.** Communicating spaces can open directly into the large-volume space or can connect through open passageways.

**A.1.4.6 First Indication of Smoke.** See Figure A.1.4.6.

For design evaluations using physical or CFD modeling, a method to define the smoke interface height and the first indication of smoke using a limited number of point measurements over the height of the atrium is required. One approach [54, 64] uses linear interpolation of the point measurements. Using temperature data, the interfaces are at the heights at which the temperature is as follows:

$$T_n = C_n(T_{max} - T_b) + T_b$$

where:

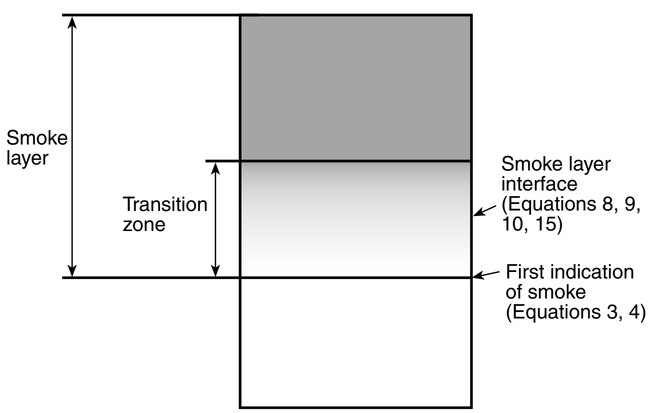
$T_n$ = temperature at the interface height

$T_{max}$ = temperature in the smoke layer

$T_b$ = temperature in the cold lower layer

$C_n$ = interpolation constant with values of 0.1–0.2 for the first indication of smoke and 0.8–0.9 for the smoke layer interface, respectively

**FIGURE A.1.4.6. Smoke layer interface.**




**A.1.4.8 Large-Volume Space.** Atria and covered malls are examples of large-volume spaces.

**A.1.4.19 Transition Zone.** See A.3.8.1.2 for further details.

**A.1.5.4.1** The performance objective of automatic sprinklers installed in accordance with NFPA 13, *Standard for the Installation of Sprinkler Systems*, is to provide fire control, which is defined as follows: Limiting the size of a fire by distribution of water so as to decrease the heat release rate and pre-wet adjacent combustibles, while controlling ceiling gas temperatures to avoid structural damage. A limited number of investigations have been undertaken in which full-scale fire tests were conducted in which the sprinkler system was challenged but provided the expected level of performance. These investigations indicate that, for a fire control situation, the heat release rate is limited but smoke can continue to be produced. However, the temperature of the smoke is reduced.

Full-scale sprinklered fire tests were conducted for open-plan office scenarios [64, 65]. These tests indicate that there is an exponential decay in the heat release rate for the sprinklered fires after the sprinklers are activated and achieve control. The results of these tests also indicate that a design fire with a steady-state heat release rate of 500 kW provides a conservative estimate for a sprinklered open-plan office.

Limited full-scale test data are available for use in determining design fire size for other sprinklered occupancies. Hansell and Morgan [66] provide conservative estimates for the convective heat release rate based on U.K. fire statistics: 1 MW for a sprinkered office, 0.5–1.0 MW for a sprinklered hotel bedroom, and 5 MW for a sprinklered retail occupancy. These steady-state design fires assume the area is fitted with standard response sprinklers.

Full-scale fire tests for retail occupancies were conducted in Australia [67]. These tests indicated that for some common retail outlets (clothing and book stores) the fire is controlled and eventually extinguished with a single sprinkler. These tests also indicated that the sprinklers might have difficulty suppressing a fire in a shop such as a toy store with a high fuel load.

Full-scale fire tests were conducted for a variety of occupancies (retail stores, cellular offices, and libraries) in the United Kingdom [70].

Full-scale fire tests were conducted for compact mobile storage systems used for document storage. Information on tests conducted in 1979 on behalf of the Library of Congress is provided in Appendix C of NFPA 909, *Standard for the Protection of Cultural Resources, Including Museums, Libraries, Places of Worship, and Historic Properties.* Subsequent full-scale fire tests conducted for the Library of Congress Archives II and the National Library of Canada showed that fires in compact mobile storage systems are difficult to extinguish [68].

**A.1.5.4.2** During the initial active phase of the fire with the sprinklers operating, the smoke layer remains stratified under the ceiling [49]. Near the sprinklers, smoke is pulled into the cold lower layer by the water droplets and returns to the smoke layer due to buoyancy. Once the sprinklers gain control and begin to suppress the fire, the gas temperature in the smoke layer falls rapidly and the smoke is dispersed throughout the volume as buoyancy decays.

**A.1.5.4.3** The temperature of smoke produced in a sprinklered fire depends on factors such as the heat release rate of the fire, number of sprinklers operating, and sprinkler application density. Full-scale fire tests with the water temperature at 10°C indicate that, for four operating sprinklers, the smoke temperature is cooled to near or below ambient if the heat release rate is <200 kW at an application density of 0.1 gpm/ft$^2$ and <500 kW at an application density of 0.2 gpm/ft$^2$. For higher heat release rates, the smoke temperature is above ambient and is buoyant as it leaves the sprinklered area.

For low heat release rate sprinkered fires, the smoke is mixed over the height of the compartment. The smoke flow through large openings into an atrium has a constant temperature with height.

With higher heat release rates, a hot upper layer is formed. The temperature of the upper layer will be between the ambient temperature and the operating temperature of the sprinkler. If the smoke is hotter than the sprinkler operating temperature, further sprinklers will be activated and the smoke will be cooled. For design purposes, a smoke temperature equivalent to the operating temperature of the sprinklers can be assumed.

**A.1.6.3** One source of data is the ASHRAE *Handbook of Fundamentals*, Chapter 26, Climatic Design Information. It is suggested that the 99.6 percent heating dry bulb (DB) temperature and the 0.4 percent cooling DB temperature be used as the winter and summer design conditions, respectively. It is also suggested that the 1 percent extreme wind velocity be used as the design condition. Where available, more site-specific data should be consulted.

**A.2.4.1.3** A computer model (written in a programming language or using a spreadsheet) can be constructed using the algebraic equations contained in Chapter 3 in order to calculate the position of a smoke layer interface over time, with and without smoke exhaust. This approach involves the calculation of the mass flow rate of smoke entering the smoke layer, the temperature of the smoke entering the layer, and the mass flow rate of smoke removed from the smoke layer by mechanical or gravity venting. The steps used to calculate the position of the smoke layer interface are as follows:

(1) Select the time step for the calculation, $\Delta t$.

(2) Determine the design fire (e.g., steady, growing fire, growing fire with steady maximum, or other description of heat release rate as a function of time). *(See 3.2.3 for a discussion of growing fires.)*

(3) Calculate or specify the heat release rate, $Q$, of the design fire at the current time step as well as the convective portion of the heat release rate, $Q_c$.

(4) Calculate the mass flow rate of smoke entering the smoke layer during the current time step. For an axisymmetric plume, the plume mass flow rate should be calculated from either Equation (8) or Equation (9), depending on the position of the smoke layer at the end of the previous time step relative to the flame height of the design fire. For a balcony spill plume, the plume mass flow rate should be calculated from Equation (10). For a window plume, the plume mass flow rate should be calculated from Equations (13), (14), and (15). For an unsteady fire, the plume mass flow rate should be evaluated at the heat release rate at midpoint of the time step.

(5) Calculate the temperature of the smoke entering the smoke layer using Equation (17).

(6) Calculate the mass of smoke in the smoke layer at the end of this time step.

$$M_2 = M_1 + (m_2 - m_1)\Delta t$$

where:

$M_2$ = mass of smoke in the smoke layer at the end of current time step (kg)

$M_1$ = mass of smoke in the smoke layer at the start of current time step (kg)

$m_2$ = mass flow rate of plume (kg/sec)

$m_1$ = mass flow rate of exhaust (kg/sec)

$\Delta t$ = time step (sec)

(7) Calculate the new temperature of the smoke layer based on conservation of energy.

$$T_{s,2} = T_{s,1} + [(1-\eta)m_p(T_p - T_o) - m_e(T_s - T_o) - (T_s - T_o)(m_p - m_e)]\frac{\Delta t}{M_1}$$

where:

$T_{s,2}$ = smoke layer temperature at the end of current time step (°C)

$T_{s,1}$ = smoke layer temperature at the start of current time step (°C)

$T_p$ = temperature of plume (°C)

$T_o$ = ambient temperature (°C)

$\eta$ = heat loss factor (dimensionless)

$M_p$ = mass flow rate of plume (kg/sec)

$M_e$ = mass flow rate of exhaust (kg/sec)

The heat loss factor is the fraction of the convective heat release rate that is transferred from the smoke layer to the ceiling and walls, and it has a maximum value of 1.0. The maximum temperature rise occurs where the heat loss factor is zero.

(8) Calculate the density of the smoke layer:

$$\rho_s = \frac{1.2(T_o + 273)}{T_2 + 273}$$

where $\rho_s$ is the density of the smoke layer at the end of the time step (kg/m$^3$).

(9) Calculate the volume of the smoke layer:

$$V_2 = \frac{M_2}{\rho_s}$$

where $V_2$ is the volume of the smoke layer at the end of the time step (m$^3$).

(10) Determine the new smoke layer interface position as a function of the upper layer volume and the geometry of the smoke reservoir. For constant cross-sectional areas, the smoke layer position is calculated as follows:

$$z_2 = H_{ceiling} - \frac{V_2}{A_{reservoir}}$$

where:

$z_2$ = smoke layer interface height above floor (m)

$H_{ceiling}$ = ceiling height above floor (m)

$A_{reservoir}$ = area of reservoir (m$^2$)

(11) Stop calculations if the maximum number of time steps has been reached or if the smoke layer interface is at or below the top of the fuel.

(12) Return to step (3) and use the newly calculated values for the calculations of the next time step.

**A.3.1.1.3** Common simplifications of zone models are listed in Table A.3.1.1.3(a).

Verifying computer fire model results is important because it is sometimes easier to obtain results than to determine their accuracy. Computer fire model results have been verified over a limited range of experimental conditions [42, 43, 44]; review of these results should provide the user with a level of confidence. However, because the very nature of a fire model's utility is to serve as a tool for investigating unknown conditions, there will be conditions for which any model has yet to be verified. It is for these conditions that the user should have some assistance in judging the model's accuracy.

There are three areas of understanding that greatly aid accurate fire modeling of unverified conditions. The first area involves understanding what items are being modeled. The second area involves appropriately translating the real-world items into fire model input. The third area involves understanding the model conversion of input to output.

The items the modeler must accurately characterize are the fuel, the compartment, and the ambient conditions, as indicated in Table A.3.1.1.3(b). The fuel heat-release rate is an important feature to describe. There are many other details of the fuel that also affect fire growth, such as species production, radiative heat loss fraction, fuel-to-air combustion ratio, and heat of combustion. However, the desired accuracy of the answer dictates which of these should be included and which can be ignored. Compartment vent descriptions must also be properly evaluated. Often, leakage areas can account for substantial, unanticipated gas flows, especially in instances of extreme weather conditions with regard to temperature or wind.

Translating actual characteristics into a format recognizable as model input is the second major area of fire modeling. Some items simply do not merit attention because of their lower-order effects. Other items must be represented in ways that are altered somewhat. An example of the first case is excluding a mechanical ventilation duct when a large door to a room remains open. An example to the second case is a fire burning along a 5-ft vertical section of wall. The height of the fire is best described as the floor level, the lowest point where flames can entrain air.

The last area of understanding is perhaps the most difficult for the novice to master; this pertains to understanding how the model converts input to output. It is not practical for the new user to grasp every detail of this transformation process, but it is possible for the novice to anticipate many results with a basic comprehension of fire dynamics [39, 40] and working knowledge of the three conservation laws [41]. The conservation laws can be expressed with differential equations to reproduce the smooth, continuous changes exhibited by properties behaving in real fires. To the degree that the mathematics deviates from the differential representation of the conservation laws, the more uncertain the model accuracy becomes outside the range of verification. The potential for model inaccuracy is affected by the relative influence of the particular term in the equation. Terms having the greatest influence contain variables that are raised to exponential powers greater than one.

Algebraic correlations, other fire models, scale models, and common sense can be used to verify model accuracy. The algebraic equations are only verified given the experimental conditions from which they were correlated. Projections beyond these experimental domains can be based on trends at the experimental endpoints. Using one model to verify another model ensures precision but not necessarily accuracy, unless the second model was independently verified.

Experimental scale models can always be used to verify computer model results. Reduced scale models are the most economical; trends are easily obtainable from such measurements but refined data less readily so.

**Table A.3.1.1.3(a) Simplifications in Zone Models**

**Fuel**

- Heat release rate isn't accelerated by heat feedback from smoke layer.
- Post-flashover heat release rate is weakly understood, and its unique simulation is attempted by only a few models.
- CO production is simulated, but its mechanism is not fully understood through the flashover transition.
- Some models do not consider burning of excess pyrolyzate on exit from a vent.

**Plumes**

- Plume mass entrainment is ±20 percent and not well verified in tall compartments.
- There is no transport time from the fire elevation to the position of interest in the plume and ceiling jet.
- Spill plume models are not well developed.
- Not all plume models consider the fuel area geometry.
- Entrainment along stairwells is not simulated.
- Entrainment from horizontal vents is not simulated by all models.

**Layers**

- Hot stagnation layers at the ceiling are not simulated.
- There is uniformity in temperature.

**Heat Transfer**

- Some models do not distinguish between thermally thin and thermally thick walls.
- There is no heat transfer via barriers from room to room.
- Momentum effects are neglected.

**Ventilation**

- Mixing at vents is correlationally determined.

**Table A.3.1.1.3(b) Simplifications in Field Models**

**Burning Fuel Description**

- Heat release rate as it changes with time
- Fire elevation
- Radiation fraction
- Species production rate
- Area of fire (line, pool, or gaseous)

**Compartment Description**

- Height of ceiling
- Size, location, and dynamic status (open or closed) of the vent (including leakage area)
- Thermophysical properties of wall, ceiling, and floor material
- Location, capacity, and status of mechanical ventilation
- Presence of beams or trusses
- Smoke transport time in the plume or ceiling jet
- Structural failure
- Initial temperature

**Ambient Conditions Description**

- Elevation
- Ambient pressure
- Ambient temperature
- Wind speed and direction
- Relative humidity
- Outside temperature

**A.3.1.2.1** A more complete review of scaling techniques and examples can be found in the referenced literature [35]. Smoke flow studies have been made by Heskestad [36] and Quintiere, McCaffrey, and Kashiwagi [37]. Analog techniques using a water and saltwater system are also available [38]. Smoke flow modeling for buildings is based on maintaining a balance between the buoyancy and convective "forces" while ignoring viscous and heat conduction effects. Neglecting these terms is not valid near solid boundaries. Some compensation can be made in the scale model by selecting different materials of construction.

**A.3.1.2.2** Dimensionless groups can be formulated for a situation involving a heat source representing a fire along with exhaust and make-up air supply fans of a given volumetric flow rate. The solution of the gas temperature ($T$), velocity ($v$), pressure ($p$), surface temperature ($T_s$) expressed in dimensionless terms and as a function of $x$, $y$, $z$, and time ($t$) are:

$$\begin{Bmatrix} \dfrac{T}{T_o} \\ \dfrac{v}{\sqrt{gl}} \\ \dfrac{p}{\rho_o gl} \\ \dfrac{T_s}{T_o} \end{Bmatrix} = f\left(\frac{x}{l}, \frac{y}{l}, \frac{z}{l}, \frac{t}{\sqrt{l/g}}, \Pi_1, \Pi_2, \Pi_3\right)$$

where:

$l$ = a characteristic length
$g$ = gravitational acceleration
$T_o$ = ambient temperature
$\rho_o$ = ambient density

$\Pi_1$, $\Pi_2$, and $\Pi_3$ are dimensionless groups arising from the energy release of the fire, fan flows, and wall heat transfer:

$$\Pi_1 = \frac{Q}{\rho_o c_p T_o \sqrt{g} l^{5/2}} \sim \frac{\text{fire energy}}{\text{flow energy}}$$

where:

$Q$ = energy release rate of the fire
$c_p$ = specific heat of the ambient air

$$\Pi_2 = \frac{V_{fan}}{\sqrt{g} l^{5/2}} \sim \frac{\text{fan flow}}{\text{buoyant flow}}$$

where $V_{fan}$ = volumetric flow rate of the exhaust fan.

$$\Pi_3 = \frac{1}{(k\rho c)_w} \left\{\frac{\rho_o}{\mu}\right\}^{1.6} g^{0.3} k^2 l^{0.9} \sim \frac{\text{convection heat transfer}}{\text{wall heat transfer}}$$

where:

$(k\rho c)_w$ = thermal properties (conductivity, density, and specific heat) of the wall
$\mu$ = gas viscosity
$k$ = gas thermal conductivity

The expression of $\Pi_3$ is applicable to a thermally thick construction material. Additional dimensionless terms ($\Pi$s) are needed if wall thickness and radiation effects are significant. $\Pi_3$ attempts to correct for heat loss at the boundary by permitting a different construction material in the scale model in order to maintain a balance for the heat losses.

For a typical building, the recommended minimum geometric scaling should be $^1/_8$.

The scaling expression for the fire heat-release rate follows from preserving $\Pi_1$. Similarly, expressions for the volumetric exhaust rate and wall thermal properties are obtained from preserving $\Pi_2$ and $\Pi_3$. The wall properties condition is easily met by selecting a construction material that is noncombustible and closely matches $(k\rho c)_w$ with a material of sufficient thickness to maintain the thermally thick condition.

The following examples are included to provide insight into the way that the Froude modeling scaling relations are used.

*Example 1.* What scale model should be used for a mall where the smallest area of interest, at 3 m, is the floor-to-ceiling height on the balconies?

Note that it is essential that the flow in the model is fully developed turbulent flow, and to achieve this it is suggested that areas of interest in the scale model be at least 0.3 m. The corresponding floor-to-ceiling height of the model should be at least 0.3 m. Set $l_m$ = 0.3 m and $l_F$ = 3 m, then $l_m/l_F$ = 0.1. Therefore, the model can be one-tenth scale.

*Example 2.* The design fire for a specific facility is a constant fire of 5000 kW. What size fire will be needed for a one-tenth scale model?

$$\frac{l_m}{l_F} = 0.1$$

$$Q_m = Q_F\left(\frac{l_m}{l_F}\right)^{5/2} = 5000(0.1)^{5/2} = 15.8 \text{ kW}$$

*Example 3.* For a full-scale facility with a smoke exhaust rate of 250 $m^3$/sec, what is the smoke exhaust rate for a one-tenth scale model?

$$V_{fan,m} = V_{fan,F}\left(\frac{l_m}{l_F}\right)^{5/2} = 250(0.1)^{5/2} = 7.9 \text{ m}^3/\text{sec}$$

*Example 4.* The walls of a full-scale facility are made of concrete. What is the impact of constructing the walls of a one-tenth scale model of gypsum board?

The $k\rho c$ of brick is 1.7 $kW^2/m^{-4} \cdot K^{-2} \cdot s$.

The ideal thermal properties of the model can be calculated as

$$(k\rho c)_{w,m} = (k\rho c)_{w,F}\left(\frac{l_m}{l_F}\right)^{0.9} = (1.7)(0.1)^{0.9} =$$

$$0.21(\text{kW}^2/\text{m}^{-4} \cdot \text{K}^{-2} \cdot \text{sec})$$

The value for gypsum board is 0.18 $kW^2/m^{-4} \cdot K^{-2} \cdot s$, which is close to the ideal value above, so that the gypsum board is a good match. It should be noted that using glass windows for video and photographs would be more important than scaling of thermal properties.

*Example 5.* In a one-tenth scale model, the following clear heights were observed: 2.5 m at 26 seconds, 1.5 m at 85 seconds, and 1.0 m at 152 seconds. What are the corresponding clear heights for the full-scale facility?

For the first clear height and time pair of $z_m$ = 2.5 m at $t_m$ = 26 seconds:

$$z_F = z_m\left(\frac{l_F}{l_m}\right) = 2.5(10/1) = 25 \text{ m}$$

and

$$t_F = t_m\left(\frac{l_F}{l_m}\right)^{1/2} = 26(10/1)^{1/2} = 82 \text{ sec}$$

The other clear height and time pairs are calculated in the same manner, and they are all listed below:

| Scale Model Observation | | Full-Scale Facility Prediction | |
|---|---|---|---|
| Clear Height (m) | Time (sec) | Clear Height (m) | Time (sec) |
| 2.5 | 26 | 25 | 82 |
| 1.5 | 85 | 15 | 269 |
| 1.0 | 152 | 10 | 480 |

**A.3.2.1** A design fire size of approximately 5000 Btu/sec for mercantile occupancies is often referenced [1]. This is primarily based on a statistical distribution of fire sizes in shops (retail stores) in the United Kingdom that included sprinkler protection. Less than 5 percent of fires in this category exceeded 5000 Btu/sec. Geometrically, a 5000-Btu/sec fire in a shop has been described as a 10-ft square resulting in an approximate heat-release rate per unit area of 50 Btu/sec-ft$^2$.

**A.3.2.2.1** Full-scale fire tests for open-plan offices [64, 65] have shown that, once the sprinklers gain control of the fire but are not immediately able to extinguish it due to the fuel configuration, the heat release rate decreases exponentially as follows:

$$Q(t) = Q_{act}e^{-kt}$$

where:

$Q(t)$ = heat release rate at time $t$, after sprinkler activation (Btu/sec)

$Q_{act}$ = heat release rate at sprinkler activation (Btu/sec)

$t$ = time after sprinkler activation (sec)

$k$ = decay constant (sec$^{-1}$)

Estimates for the decay constant for office occupancies protected with a discharge density of 0.1 gpm/ft$^2$ are 0.0023 for situations with light fuel loads in shielded areas [64] and 0.00155 sec$^{-1}$ for situations with heavy loads [65].

**A.3.4** Another case for which a solution has been developed is depicted in Figure A.3.4. In this case, the ambient interior air within the large space has a constant temperature gradient (temperature change per unit height) from floor level to ceiling. This case is less likely than temperatures that approximate a step function. For the linear temperature profile, the maximum height that smoke will rise can be derived from the pioneering work of Morton, Taylor, and Turner [11]:

$$z_m = 14.7 Q_c^{1/4}(\Delta T/dz)^{-3/8}$$

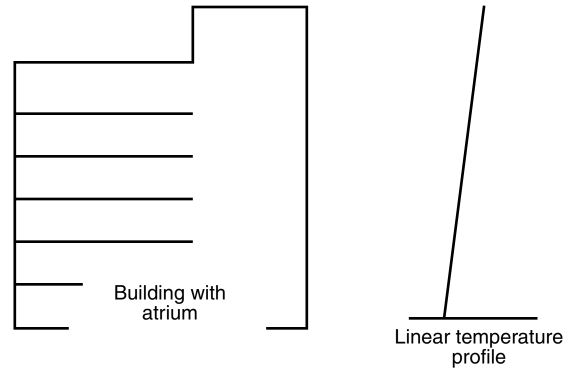
where:

$z_m$ = maximum height of smoke rise above fire surface (ft)

$Q_c$ = convective portion of the heat release rate (Btu/sec)

$\Delta T/dz$ = rate of change of ambient temperature with respect to height (°F/ft)

**FIGURE A.3.4 Unusual case of linear temperature profile.**




The convective portion of the heat release rate, $Q_c$, can be estimated as 70 percent of the total heat release rate.

The minimum $Q_c$ required to overcome the ambient temperature difference and drive the smoke to the ceiling ($z_m = H$) follows readily from the preceding equation:

$$Q_{c,\min} = 2.39 \times 10^{-5} H^{5/2} \Delta T_o^{3/2}$$

where:

$Q_{c,\min}$ = minimum convective heat release rate to overcome stratification (Btu/sec)

$H$ = ceiling height above fire surface (ft)

$\Delta T_o$ = difference between ambient temperature at the ceiling and ambient temperature at the level of the fire surface

Alternatively, an expression is provided in terms of the ambient temperature increase from floor to ceiling, which is just sufficient to prevent a plume of heat release, $Q_c$, from reaching a ceiling of height, $H$:

$$\Delta T_o = 1300 Q_c^{2/3} H^{5/3}$$

Finally, as a third alternative, the maximum ceiling clearance to which a plume of strength, $Q_c$, can rise for a given $\Delta T_o$ follows from rewriting the preceding equation:

$$H_{\max} = 74 Q_c^{2/5} \Delta T_o^{3/5}$$

**A.3.5** For design purposes, the topic of algebraic equations for gas concentrations and obscuration of visibility can be addressed for two limit cases:

(1) The smoke filling scenario, where all products of combustion are assumed to accumulate in the descending smoke layer
(2) The quasi-steady vented scenario, where a quasi-steady balance exists between the rates of inflow into and outflow from the smoke layer

Normally, the quasi-steady vented scenario is of interest for design purposes because this scenario represents the quasi-steady conditions that develop with a smoke extraction system operating. The smoke filling scenario might be of interest to analyze the conditions that can develop before the smoke extraction system is actuated. A transient period exists between these two limit cases. During this transient intermediate period, the smoke layer is both filling and being exhausted. Analysis of this transient period generally requires numerical computer-based approaches. From a design standpoint, this period should be of little consequence since it is not a limit case, so it is not addressed further.

Methods to analyze the gas composition and optical characteristics for the two limit cases can be addressed in terms of a number of algebraic equations. These algebraic equations are exact, but the data used in these equations are uncertain [55]. The user should be made aware of these uncertainties to the extent they are known.

**Smoke Filling Stage — Optical Properties Analysis**

The average optical density of the descending smoke layer can be estimated if the mass optical density of the fuel can be reasonably estimated. Equation (A.1) is used to estimate the optical density as a function of the mass optical density, the mass of fuel consumed, and the volume of the smoke layer.

$$D = \frac{D_m m_f}{V_u} = \frac{D_m \int_0^t \dot{m}_f \, dt}{A z_u(t)} \quad \text{(A.1)}$$

where:

$D_m$ = mass optical density (ft$^2$/lb) (m$^2$/kg)
$\dot{m}_f$ = burning rate of fuel (lb/sec) (kg/sec)
$m_f$ = total fuel mass consumed (lb) (kg)
$A$ = horizontal cross-sectional area of atrium (ft$^2$) (m$^2$)
$z_u$ = depth of upper layer (ft) (m)
$V_u$ = volume of upper layer (ft$^3$) (m$^3$)

For the case of a flat ceiling, negligible plume area, and a fire with constant mass and heat-release rates, Equation (A.1) evaluates as

$$D = \frac{D_m Q t}{\chi_a \Delta H_c A_u H} \left[ 1 - \left( 1 + \frac{2t}{3\tau} \right)^{-3/2} \right]^{-1} \quad \text{(A.2)}$$

$$\tau = \frac{V}{V_{ent}} = \frac{AH}{k_v Q^{1/3} H^{5/3}} = \frac{AH}{k_v (\alpha_n t^n)^{1/3} H^{5/3}} \quad \text{(A.3)}$$

where:

$V$ = volume of atrium (ft$^3$) (m$^3$)
$V_{ent}$ = volumetric rate of air entrainment (ft$^3$/sec) (m$^3$/sec)
$k_v$ = volumetric entrainment constant (0.32 ft$^{4/3}$/Btu$^{1/2}$sec$^{2/3}$) (0.064 m$^{4/3}$/kW$^{1/3}$sec)
$Q$ = heat-release rate from fire (Btu/sec) (kW)
$\Delta H_c$ = heat of combustion (Btu/lb) (kJ/kg)
$H$ = height of ceiling above floor (ft) (m)
$\chi_a$ = combustion efficiency

For the case of a flat ceiling, negligible plume area, and a $t$-squared fire, Equation (A.1) evaluates as

$$D = \frac{D_m \alpha t^3}{3 \chi_a \Delta H_c A H} \left[ 1 - \left( 1 + \frac{2 k_v \alpha^{1/3} t^{5/3} H^{2/3}}{5A} \right)^{-3/2} \right]^{-1} \quad \text{(A.4)}$$

where $\alpha$ = fire growth rate = 1000/$(t_g)^2$ (sec).

For other scenarios, appropriate values must be substituted into Equation (A.1). For some scenarios, numerical integration might be necessary.

**Smoke Filling Stage — Layer Composition Analysis**

Analysis of the composition of the smoke layer is analogous in many respects to the analysis of the optical density of the layer. To analyze the smoke layer composition as a function of time, a yield factor, $f_i$, must first be assigned for each species $i$ of interest:

$$\dot{m}_i = f_i \dot{m}_f \quad \text{(A.5)}$$

where $f_i$ = yield factor (lb$_{product}$/lb$_{fuel}$) (kg$_{product}$/kg$_{fuel}$).

The mass fraction, $Y_i$, of each species in the smoke layer is

$$Y_i = \frac{m_i}{\Sigma_i m_i} \quad \text{(A.6)}$$

where $Y_i$ = mass fraction (lb$_{species}$/lb$_{total}$) (kg$_{species}$/kg$_{total}$).

The term in the numerator of Equation (A.6) is calculated, similar to Equation (A.1), as

$$m_i = \int_0^t \dot{m}_i \, dt = \int_0^t f_i \dot{m}_f \, dt = \int_0^t f_i \frac{Q}{\chi_a \Delta H_c} \, dt \quad \text{(A.7)}$$

For the case of a constant yield factor and a $t$-squared fire growth rate, Equation (A.7) evaluates as

$$\dot{m}_i = f_i \int_0^t \frac{\alpha t^2}{\chi_a \Delta H_c} \, dt = \frac{f_i \alpha t^3}{3 \chi_a \Delta H_c} \quad \text{(A.8)}$$

For the case of a constant yield factor and a steady fire, Equation (A.7) evaluates as

$$m_i = \int_0^t f_i \frac{Q}{\chi_a \Delta H_c} \, dt = \frac{f_i Q t}{\chi_a \Delta H_c} \quad \text{(A.9)}$$

The term in the denominator of Equation (A.6) represents the total mass of the smoke layer. Typically, the mass of fuel released is negligible compared to the mass of air entrained into the smoke layer, so the total mass of the smoke layer can be approximated as

$$\sum_i m_i = \bar{\rho} V_u \frac{\rho_o T_o V_u}{\bar{T}} \quad \text{(A.10)}$$

For the case where the temperature rise of the smoke layer is small relative to the ambient absolute temperature (i.e., $\bar{T}/T_o \approx 1$), Equation (A.10) reduces to

$$\sum_i m_i = \rho_o V_u \tag{A.11}$$

Substituting Equations (A.8) and (A.11) into Equation (A.6) yields, for the *t*-squared fire,

$$Y_i = \frac{f_i \alpha t^3}{3\rho_o V_u \chi_a \Delta H_c} \tag{A.12}$$

Substituting Equations (A.9) and (A.11) into Equation (A.6) yields, for the steady fire,

$$Y_i = \frac{f_i Q t}{\rho_o V_u \chi_a \Delta H_c} \tag{A.13}$$

For a fire that grows as a *t*-squared fire from $Q = 0$ at time $t = 0$ to $Q = Q_{qs}$ at time $t = t_{qs}$, then continues to burn indefinitely at $Q = Q_{qs}$, Equations (A.12) and (A.13) can be combined to yield

$$Y_i = \frac{f_i[\alpha t_{qs}^3/3 + Q_{qs}(t - t_{qs})]}{\rho_o V_u \chi_a \Delta H_c} \tag{A.14}$$

The volume of the smoke layer, $V_u$, in these equations is evaluated by the methods presented in Section 3.8 with $V_u = A(H - z)$.

### Quasi-Steady Ventilated Stage — Optical Properties Analysis

Under quasi-steady ventilated conditions, a balance exists between the rate of mass inflow into the smoke layer and the rate of mass outflow from the smoke layer. The average optical density of the smoke layer can be calculated on a rate basis as

$$D = \frac{D_m \dot{m}_f}{V} = \frac{D_m Q}{\chi_a \Delta H_c V} \tag{A.15}$$

Equation (A.15) can be used to determine the average optical density of the smoke layer for a given exhaust rate. Alternatively, the required exhaust rate needed to produce a particular optical density, $D$, can be determined by rearranging Equation (A.15) as

$$V = \frac{D_m Q}{D \chi_a \Delta H_c} \tag{A.16}$$

Use of Equations (A.15) and (A.16) requires knowledge of the mass optical density, $D_m$, of the smoke. Mass optical densities for a variety of fuels are reported by Tewarson [21] and by Mulholland [60].

Values reported by these investigators are based on small-scale fire tests, generally conducted under well-ventilated conditions. It should be recognized that the optical properties of smoke can be affected by ventilation, so it is not clear how well these small-scale data correlate with large-scale behavior, particularly for scenarios where the large-scale conditions include underventilated fires. This topic requires further research.

### Quasi-Steady Ventilated Stage — Layer Composition Analysis

The mass fraction of each species $i$ in the smoke layer under quasi-steady flow conditions is given in general by

$$Y_i = \frac{\dot{m}_1}{\Sigma_i \dot{m}_i} \tag{A.17}$$

Under quasi-steady flow conditions, the mass flow rate of each species is given as

$$\dot{m}_i = f_i \dot{m}_f = f_i \frac{Q}{\chi_a \Delta H_c} \tag{A.18}$$

The total mass flow rate under quasi-steady conditions is given by

$$\sum_i \dot{m}_i = \bar{\rho} V = \rho_o V_{ent} = \rho_o (V - V_{exp}) \tag{A.19}$$

Substituting Equations (A.18) and (A.19) into Equation (A.17) permits calculation of the mass fraction for each species $i$ of interest in terms of a known exhaust rate.

$$Y_i - Y_{i,o} = \frac{f_i Q}{\rho_o \chi_a \Delta H_c (V - V_{exp})} \tag{A.20}$$

To determine the required volumetric exhaust rate needed to limit the mass fraction of some species $i$ to a limit value, $Y_i$, Equation (A.26) is rearranged to

$$V = V_{exp} + \frac{f_i Q}{\rho_o \chi_a \Delta H_c (Y_i - Y_{i,o})} \tag{A.21}$$

The volumetric expansion rate, $V_{exp}$, is calculated as

$$V_{exp} = \frac{Q_n}{\rho_o c_p T_o} = \frac{(1 - \chi_i) Q}{\rho_o c_p T_o} \tag{A.22}$$

**A.3.6** Limiting the size and distribution of the exhaust fan inlets is intended to prevent the smoke from cooling before it can be exhausted by keeping the layer up near the ceiling. This is particularly important for spaces where the length is greater than the height, such as shopping malls.

Fan inlets should be distributed because a high exhaust rate at any one point in thin layers could cause fresh air from below the smoke layer to be drawn through the layer, creating the reverse situation of a bathtub drain. The objective of distributing the fan inlets is therefore to establish a gentle and a generally uniform exhaust rate over the entire smoke layer.

**A.3.6.2.2** Equations (3) and (4) are empirically based for estimating the smoke layer interface position during the smoke filling process. This review of Equations (3) and (4) is divided into two parts:

(1) Comparison of the results of both Equations (3) and (4) with those from theoretically based equations (with empirically determined constants), hereafter referred to as ASET-based equations
(2) Evaluation of the predictive capability of Equation (3) and an ASET-based equation by comparing the output from the equations with experimental data

**Comparisons with ASET-Based Equations**

Comparisons of the NFPA 92B equations for smoke filling with ASET-based equations provide an indication of the differences between empirically based equations, for example, Equations (3) and (4), with those that are based principally on theory.

**Steady Fires**

A theoretically based equation for smoke filling can be derived using the laws of conservation of mass and energy to determine the additional volume being supplied to the upper layer [55]. Using Zukoski's plume entrainment correlation [56],

$$\frac{z}{H} = \left[1 + \frac{2k_v(tQ^{1/3}/H^{4/3})}{3(A/H^2)}\right]^{-3/2} \qquad \text{(A.23)}$$

where:

$z$ = smoke layer interface position (m)
$H$ = ceiling height (m)
$t$ = time from ignition (sec)
$Q$ = heat-release rate (kW)
$A$ = cross-sectional area of space ($m^2$)
$k_v$ = entrainment constant ≈ 0.064 $m^{4/3}$/(sec-$kW^{1/3}$)

A comparison of $z/H$ predicted by Equations (3) and (A.23) is presented in Figure A.3.6.2.2(a) for a ceiling height of 30 m, a steady fire size of 5 MW, and a wide range of $A/H^2$ ratios. In general, the agreement between the two equations is reasonable. Equation (3) predicts a lower smoke layer interface position at most times, except in the case of the voluminous space represented by $A/H^2$ of 10. In this case, Equation (3) indicates a delay of approximately 100 seconds before a layer forms, while Equation (A.23) indicates immediate formation of the layer. Such a delay is reasonable for such a large space. This delay can be addressed by including an additional term in Equation (A.23) to account for the transport lag [48]. The transport lag is estimated as 37 seconds for this case with a height of 30 m and cross-sectional area of 9000 $m^2$.

While the comparison in Figure A.3.6.2.2(a) is useful, it applies only to selected values of $A$, $H$, and $Q$. This comparison can be generalized for all values of $A$, $H$, and $Q$ by forming a ratio of the two equations expressed in terms of $t$:

$$\frac{t_{eqnA.23}}{t_{eqn3}} = \frac{3}{2k_v}\,\frac{[(z/H)^{-2/3} - 1]}{\exp\left[\dfrac{1.11 - z/H}{0.28}\right]} \qquad \text{(A.24)}$$

**FIGURE A.3.6.2.2(a) Comparison of algebraic equations, Equations (3) and (A.23): steady fire.**

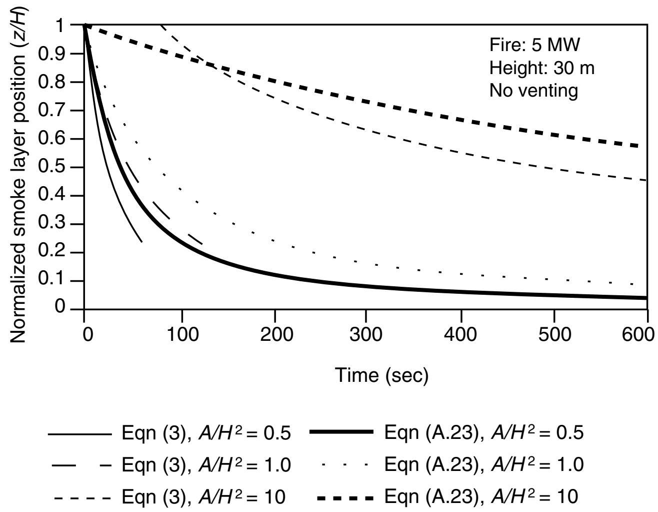
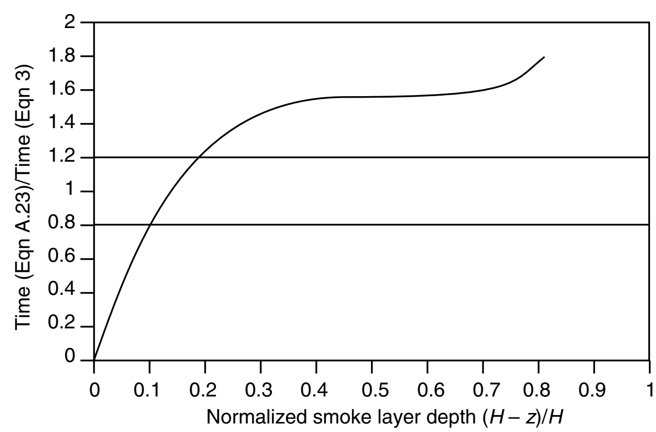



Figure A.3.6.2.2(b) indicates the relationship of the time ratio with the normalized smoke layer depth, $(H - z)/H$. For perfect agreement between the two equations, the time ratio should have a value of 1.0. However, the time ratio varies appreciably. The time ratio is within 20 percent of 1.0 only for a very small range. For normalized smoke layer depths less than 0.13 (or a normalized clear height of 0.87), Equation (A.23) always predicts a shorter time to reach a particular depth than Equation (3). Conversely, Equation (3) predicts shorter times to attain any normalized smoke layer depth in excess of 0.13.

**FIGURE A.3.6.2.2(b) Comparison of algebraic equations, Equations (3) and (A.23): steady fire.**




The time ratio is relatively insensitive for values of $(H - z)/H$, ranging from 0.4 to 0.6. Within this range, the time ratio is nominally 1.5, that is, the time predicted by Equation (A.23) to obtain a smoke layer of a particular depth is 50 percent greater than that predicted by Equation (3). Alternatively, Equation (3) predicts a more rapid descent to this range of smoke layer depths than Equation (A.23).

### *t*-squared Fires

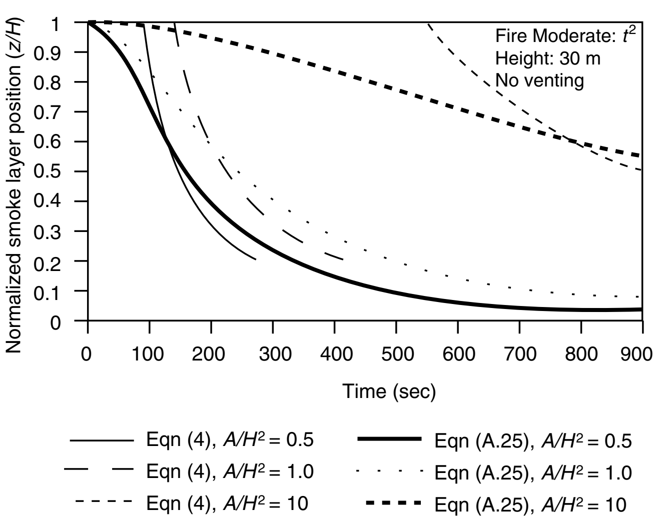
A similar comparison of the empirically based Equation (4) and a theoretically based equation for *t*-squared fires can be conducted. The ASET-based equation is

$$\frac{z}{H} = \left(1 + \frac{20 k_v t^{5/3} / H^{-4/3}}{t_g^{2/3} A / H^2}\right)^{-3/2} \quad \text{(A.25)}$$

where $t_g$ = fire growth rate (sec).

A comparison of the predicted $z/H$ values are presented in Figure A.3.6.2.2(c) for a ceiling height of 30 m, a moderate fire growth rate ($t_g$ = 300 seconds), and a wide range of $A/H^2$ ratios. For values of $A/H^2$ up to 1.0, the agreement appears very reasonable once the smoke layer has formed. Again, the empirically derived equation implicitly includes the transport lag. For $A/H^2$ of 10.0, the delay for a smoke layer to form is greater than that for smaller $A/H^2$ ratios such that reasonable agreement in smoke layer interface position is not achieved until approximately 800 seconds. The estimated transport lag is 206 seconds [48].

**FIGURE A.3.6.2.2(c) Comparison of algebraic equations, Equations (4) and (A.25): *t*-squared fire.**



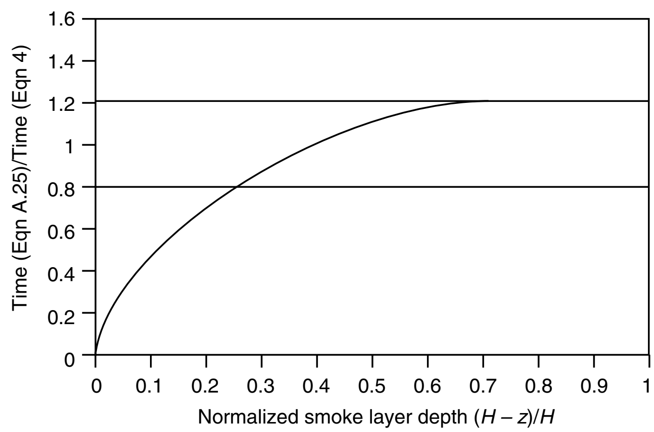

The value of $z/H$ of 0.59 for the point of intersection of the various curves for the two equations is a constant, independent of the values for *A*, *H*, and *Q*. Thus, for values of $z/H >$ 0.59, Equation (A.25) estimates a shorter time to attain a particular position of the smoke layer interface, where Equation (4) estimates a faster time for lesser values of $z/H$.

Given the different exponents on the right side of the two equations, a general comparison is again only possible by solving for the times and expressing a ratio:

$$\frac{t_{eqnA.25}}{t_{eqn4}} = \left[\frac{(0.91)^{-0.69}}{4 k_v^{-0.6}}\right] \left[\frac{[(z/H)^{-2/3} - 1]^{0.6}}{(z/H)^{-0.69}}\right] \quad \text{(A.26)}$$

The relationship of the time ratio for various normalized smoke layer depths, $(H - z)/H$, is provided in Figure A.3.6.2.2(d). In general, the agreement between the two predicted times for *t*-squared fires is much better than that for steady fires, with the predicted time using Equation (A.25) being within 20 percent of that from Equation (4) for $(H - z)/H$ values from 0.26 to 0.80. As in the case of the steady fire, the time ratio is less than 1.0 for small normalized smoke layer depths. However, in this case, the time ratio does not exceed 1.0 until the normalized smoke layer depth is at least 0.40.

**FIGURE A.3.6.2.2(d) Comparison of algebraic equations, Equations (4) and (A.25): *t*-squared fire.**




### Large-Scale Experimental Programs in Tall Ceiling Spaces

The predictive capabilities of each equation can be examined by comparing their output to experimental data.

The predictive capability of Equation (A.23) is examined by comparing the output to large-scale experimental data. Sources of the experimental data involving a range of ceiling heights from 2.4 m to 12.5 m as well as room sizes and fire scenarios are identified in Table A.3.6.2.2. Included in the table are the data sources referenced in the initial development of Equation (3) [49]. Two additional sets of experimental data have become available since the committee's initial analysis [50, 51]. Comprehensive descriptions of the test programs are provided elsewhere [14, 53–55]. Because the two additional sets of data were collected from fires in spaces with significantly greater ceiling heights than in the initial sets of data, the new sets of data are of particular interest.

The measured and predicted smoke layer positions as a function of time from the previous and two new sets of data are presented in Figure A.3.6.2.2(e). The data identified as "The Committee's" include all of the data upon which the committee based initial development of Equation (3). The new sets of data are identified separately. As indicated in the figure, the smoke layer position from the data analyzed is between that measured by NRCC and BRI. Thus, despite the differences in ceiling height, the new and initial sets of data appear to be reasonably similar. The graph labeled "NFPA 92B" depicts the predictions of Equation (3). In general, agreement between the predictions from both Equations (3) and (A.23) and the experimental data is very reasonable. Equation (3) provides a lower limit of the experimental data, including the new NRCC data. Equation (A.23) appears to predict a midrange value of the data.

**FIGURE A.3.6.2.2(e) Comparison of smoke layer position, experimental data vs. predictions.**

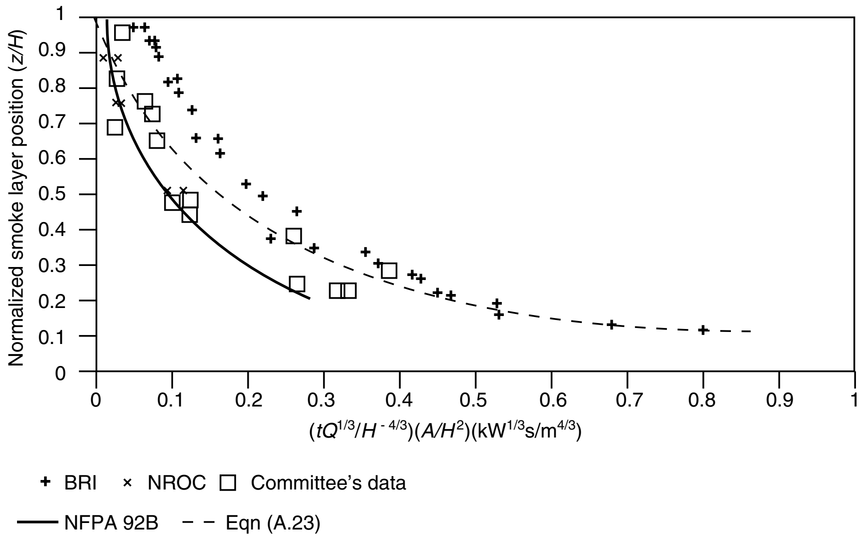



**Table A.3.6.2.2 Summary of Full-Scale Experiments**

| Research Group | Fuel | Heat Release Rate | Dimension of Test Room | Measurements of Smoke Layer Position |
|---|---|---|---|---|
| **New Data** | | | | |
| BRI [50] | Methanol pool, 3.24 m$^2$ | 1.3 MW (steady) | 30 m × 24 m, height: 26.3 m | Visual observations, first temperature rise |
| NRCC [51] | Ethanol pool, 3.6 m diameter | 8 MW (steady) | 55 m × 33 m, height: 12.5 m | First temperature rise |
| **Committee Data** | | | | |
| Sandia, Test 7 [10] | Propylene burner, 0.91 m diameter | 516 kW | 18.3 m × 12.2 m, height: 6.1 m | First temperature rise, carbon dioxide concentration |
| Mulholland [53] | Acetylene burner | 16.2 kW | 3.7 m × 3.7 m, height: 2.4 m | Temperature rise, light obscuration |
| Cooper [54] | Methane burner | 25 kW, 100 kW, 225 kW | 89.6-m$^2$ room, corridor and lobby height: 2.4 m | Temperature rise |
| Hagglund [14] | Kerosene pool, 0.5 m$^2$ | 280 kW | 5.62 m × 5.62 m, height: 6.15 m | Visual observations, first temperature rise |

Equations comparable to Equations (3) and (A.23) can be derived for variable cross-sectional areas and for fires that follow a power law (e.g., *t*-squared fires). In addition, algebraic equations pertaining to a variety of smoke layer characteristics are available, including temperature, light obscuration, and species concentration [55]. These equations are applicable to evaluating transient conditions prior to operation of the smoke management system or equilibrium conditions with an operational smoke management system. Thus, a variety of algebraic equations are available and can serve as useful tools for relatively elementary designs or as checks of specific aspects of computer calculations for more complicated situations.

**A.3.6.2.4** In the absence of an analysis using scale models, field models, or zone model adaptation, a sensitivity analysis should be considered. A sensitivity analysis can provide important information to assist in engineering judgments regarding the use of Equations (3) and (4) for complex and nonuniform geometries. An example of a sensitivity analysis is illustrated as follows for a large space having a nonflat ceiling geometry.

The first step of the analysis would be to convert a nonuniform geometry to a similar or volume-equivalent uniform geometry.

In the case of the geometry shown in Figure A.3.6.2.4(a), this would be done as follows:

(1) Convert the actual nonrectangular vertical cross-section area to a rectangular vertical cross section of equal area.
(2) The height dimension corresponding to the equivalent rectangular cross section would then be used as a substitute height factor $H_{sub}$ in Equation (4).

Results of Equation (4) should be compared with other minimum and maximum conditions as indicated by Figure A.3.6.2.4(b).

**FIGURE A.3.6.2.4(a) Large space with nonflat ceiling geometry.**

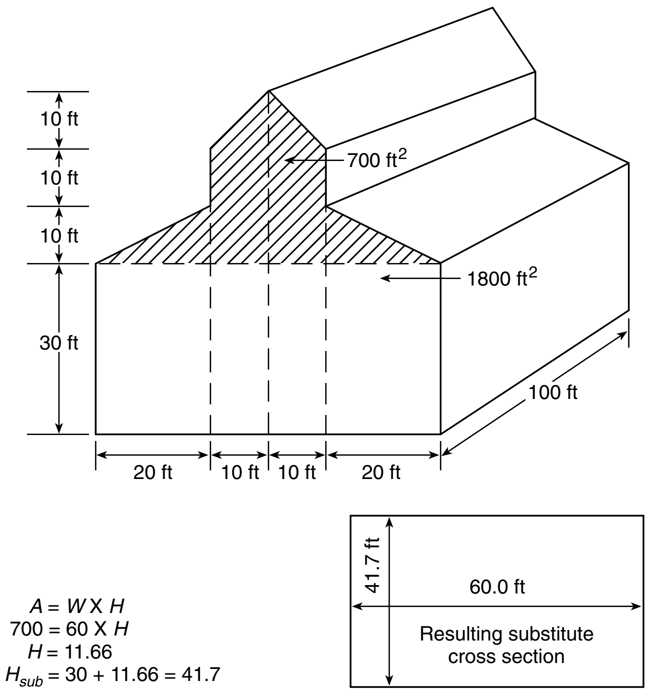



**FIGURE A.3.6.2.4(b) Other nonuniform geometry considerations.**

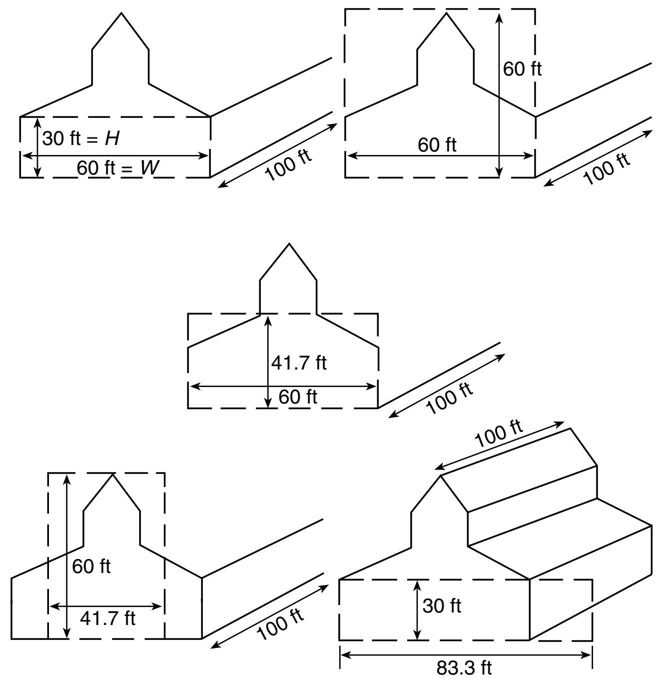
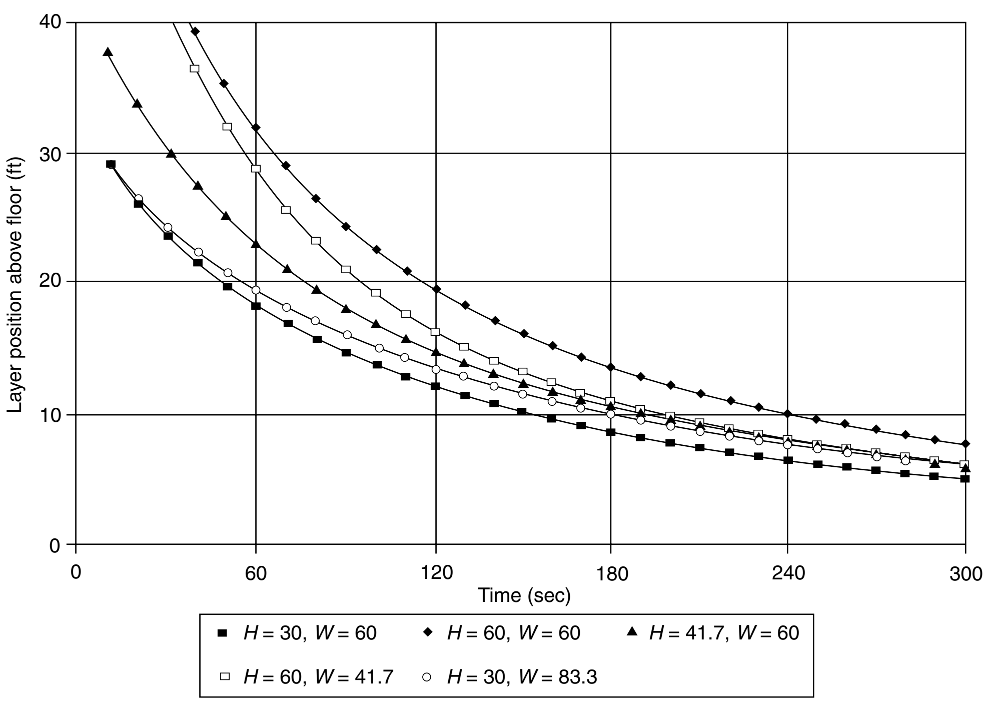



**FIGURE A.3.6.2.4(c) Comparison data for guidance on nonrectangular geometries — growing fire.**



An appropriate method of comparison could be a graph of Equation (4) as shown in Figure A.3.6.2.4(c). Assume that the building in question can be evacuated in 3 minutes and that the design criteria require the smoke layer to remain available 10 ft above the floor at this time. A review of the curves would indicate that the smoke layer heights as calculated for the substitute case are appropriate. This conclusion can be drawn by noting that neither the extreme minimum height case ($H$ = 30 ft, $W$ = 60 ft) nor the maximum height case ($H$ = 60 ft) offers an expected answer, but the results for two cases ($H$ = 41.6, $W$ = 60; and $H$ = 30, $W$ = 83.3) can be judged to reasonably approximate the behavior of the nonuniform space. It might otherwise be unreasonable to expect the behavior indicated by the maximum or minimum cases.

**A.3.6.2.4(3)** A zone model *(see 3.1.1.3.1)* predicated on smoke filling a uniform cross-sectional geometry is modified to recognize the changing cross-sectional areas of a space *(see 3.1.1)*. The entrainment source can be modified to account for expected increases or decreases in entrainment due to geometric considerations, such as projections.

**A.3.6.2.4(4)** An irregular space is evaluated using Equations (3) and (4) at and between the limits of a maximum height and minimum height identifiable from the geometry of the space using equivalent height or volume considerations.

**A.3.8.1.2** Physical model tests [71, 72] with steady-state fires have shown that Equation (8) provides a good estimate of the plume mass flow rate for an atrium smoke management system operating under equilibrium conditions *(see 3.7.1)*. The results also showed that the smoke layer was well mixed. The average temperature in the smoke layer can be approximated using the adiabatic estimate for the plume temperature at the height of the smoke layer interface [Equation (17)].

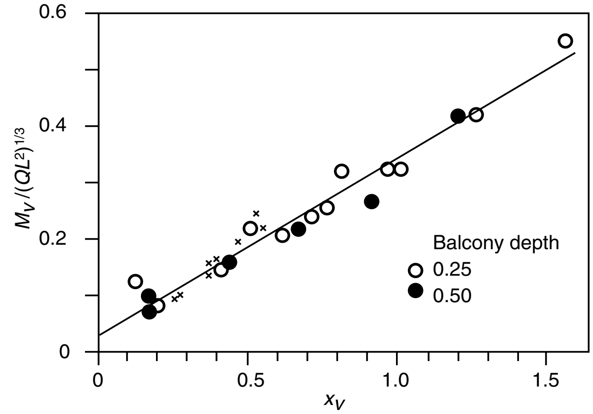
At equilibrium, the height $z$ in Equation (8) is the location of the smoke layer interface above the fuel level *(see Figure A.1.4.6)*. The transition zone is located below this level. For an efficient smoke management system, the depth of the transition zone is approximately 10 percent of the atrium height. In the transition zone, the temperature and other smoke parameters decrease linearly with height between the smoke layer interface height and the lower edge of the transition zone.

**A.3.8.2.1** Agreement of the predictions from Equation (17) with those from small-scale experimental efforts is presented in Figure A.3.8.2.1. Whereas the agreement is quite good, the results are only from two small-scale experimental programs.

**A.3.9** The equations for plugholing were originally developed for natural vents [74]. They have also been applied to a mechanical smoke exhaust system by Hinckley [62]. The numerical factors included in Equations (19) and (20) assume the exhaust inlets are located near a wall. Larger factors can be used if the inlets are located near the center of the smoke reservoir.

Although the equations were developed for natural venting, physical and numerical modeling studies conducted jointly by ASHRAE and NRC [71, 72, 73] indicate they are also applicable to mechanical exhaust systems. These studies used physical models, which were 5.5 m and 12.2 m in height with volumetric flow rates of up to 25 m$^3$/sec for a single exhaust inlet (average exhaust inlet velocities of up to 30 m/sec). The physical model results indicated that the smoke depth could be reduced to approximately 10 percent of the clear height by using multiple exhaust inlets to minimize the mass/volumetric flow rate at each exhaust inlet. The numerical model studies indicated that the results could be scaled to higher atria.

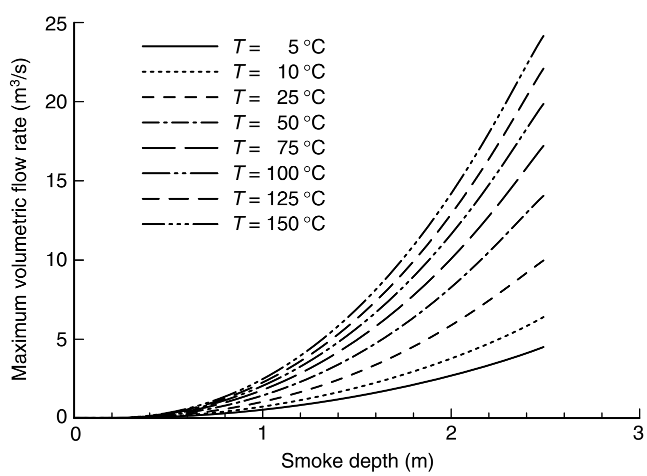
**FIGURE A.3.8.2.1 Agreement between predictions and experimental values. [17, 60]**




By increasing the number of exhaust inlets, the velocity at each exhaust inlet could be reduced. The highest efficiency for the physical model exhaust system was obtained if the inlet velocity was limited to 10 m/sec or less. It is also recommended that the ratio of the smoke layer depth to the diameter of the exhaust inlet ($d/D$) be greater than 2 ([for rectangular exhaust inlets, use $D = 2ab/(a + b)$, where $a$ and $b$ are the length and width of the exhaust opening]). In this way, the flow velocity at the bottom of the transition zone produced by the exhaust system is substantially lower than the inlet velocity and the dominant flow into the exhaust system is from the smoke layer.

Attempts to decrease the smoke layer depth below the minimum depth by using high exhaust rates were not successful. In this case, the smoke exhaust system produces a mixing of the cold air with the smoke layer. The smoke layer was cooled and diluted. However, its depth was increased.

**FIGURE A.3.9 Effect of smoke layer depth and temperature on venting rate.**




The effect of smoke layer depth and the smoke temperature on the maximum venting rate is shown in Figure A.3.9. The efficiency of the smoke exhaust system improves rapidly with increasing smoke layer depth and to a lesser extent with an increase in the smoke layer temperature. These factors, coupled with the decrease in the smoke mass flow rate with decreasing $z$, provide a self-compensating mechanism for the atrium smoke management system. The considerations outlined in this section are important when dealing with a system in which the design requirement for the clear height is just below the exhaust inlet height.

**A.3.11** Density of smoke is approximately equal to the density of air. The density of air at 68°F at sea level is 0.075 lb/ft$^3$. The density of air at another temperature can be calculated from:

$$\frac{\rho}{\rho_0} = \frac{528}{460 + T}$$

where:

$\rho_0$ = 0.075 (lb/ft$^3$)

$\rho$ = density of smoke at temperature (lb/ft$^3$)

$T$ = temperature of smoke (°F)

**A.4.4.5** Verification devices can include the following:

(1) End-to-end verification of the wiring, equipment, and devices in a manner that includes provision for positive confirmation of activation, periodic testing, and manual override operation
(2) The presence of operating power downstream of all circuit disconnects
(3) Positive confirmation of fan activation by means of duct pressure, airflow, or equivalent sensors that respond to loss of operating power; problems in the power or control circuit wiring; airflow restrictions; and failure of the belt, shaft coupling, or motor itself
(4) Positive confirmation of damper operation by contact, proximity, or equivalent sensors that respond to loss of operating power or compressed air; problems in the power, control circuit, or pneumatic lines; and failure of the damper actuator, linkage, or damper itself
(5) Other devices or means as appropriate

Items (1) through (4) describe multiple methods that can be used, either singly or in combination, to verify that all portions of the controls and equipment are operational. For example, conventional (electrical) supervision may be used to verify the integrity of the conductors from a fire alarm system control unit to the relay contact within 3 ft of the control system input *(see NFPA 72, National Fire Alarm Code®, Section 3-9)*, and end-to-end verification can be used to verify operation from the control system input to the desired end result. If different systems are used to verify different portions of the control circuit, controlled equipment, or both, then each system would be responsible for indicating off-normal conditions on its respective segment.

End-to-end verification, as described in 1.4.5, monitors both the electrical and mechanical components of a smoke control system. End-to-end verification provides positive confirmation that the desired result has been achieved during the time that a controlled device is activated. The intent of end-to-end verification goes beyond determining whether a circuit fault exists, but instead ascertains whether the desired end result (i.e., airflow or damper position) is achieved. True end-to-end verification, therefore, requires a comparison of the desired operation to the actual end result.

An "open" in a control wire, failure of a fan belt, disconnection of a shaft coupling, blockage of an air filter, failure of a motor, or other abnormal condition that could prevent proper operation is not expected to result in an off-normal indication when the controlled device is not activated, since the measured result at that time matches the expected result. If a condition that prevents proper operation persists during the next attempted activation of the device, an off-normal indication should be provided.

**A.5.3.6.2** It is an understatement to say that acceptance testing involving a real fire has obvious danger to life and property because of the heat generated and the toxicity of the smoke.

## Appendix B Predicting the Rate of Heat Release of Fires

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

**B.1 Introduction.** The following presents techniques for estimating the heat release rate of various fuel arrays likely to be present in buildings where smoke venting is a potential fire safety provision. It primarily addresses the estimation of fuel concentrations found in retail, stadia, office, and similar locations that might involve large areas addressed by this guide. Conversely, NFPA 204, *Guide for Smoke and Heat Venting*, addresses the types of fuel arrays more common to storage and manufacturing locations and other types of building situations covered by that standard. NFPA 92B is applicable to situations where the hot layer does not enhance the burning rate. The methods provided in this appendix for estimating the rate of heat release, therefore, are based on "free burning" conditions where no ceiling or hot gas layer effects are involved. And it is, therefore, assumed that the burning rate is relatively unaffected by the hot layer.

**B.2 Sources of Data.** The following sources of data appear in their approximate order of priority, given equal quality of data acquisition:

(1) Actual tests of the array involved
(2) Actual tests of similar arrays
(3) Algorithms derived from tests of arrays having similar fuels and dimensional characteristics
(4) Calculations based on tested properties and materials and expected flame flux
(5) Mathematical models of fire spread and development

**B.3 Actual Tests of the Array Involved.** Where an actual calorific test of the specific array under consideration has been conducted and the data are in a form that can be expressed as rate of heat release, the data can then be used as input for the methods in this guide. Since actual test data seldom produce the steady state assumed for a limited-growth fire or the square of time growth assumed for a continuous-growth (*t*-squared) fire, engineering judgment is usually needed to derive the actual input necessary if either of these approaches is used. *(See Appendix C for further details relevant to t-squared fires.)* If a computer model that is able to respond to a rate of heat release versus time curve is used, the data can be used directly. Currently there is no established catalog of tests of specific arrays. Some test data can be found in technical reports. Alternatively, individual tests can be conducted.

Many fire tests do not include a direct measurement of rate of heat release. In some cases, it can be derived based on measurement of mass loss rate using the following equation:

$$Q = \dot{m}h_c \qquad \text{(B.1)}$$

where:

$Q$ = rate of heat release (kW)
$\dot{m}$ = mass loss rate (kg/sec)
$h_c$ = heat of combustion (kJ/kg)

In other cases, the rate of heat release can be derived based on measurement of flame height as follows:

$$Q = 37(L + 1.02D)^{5/2} \qquad \text{(B.2)}$$

where:

$Q$ = rate of heat release (kW)
$L$ = flame height (m)
$D$ = fire diameter (m)

**B.4 Actual Tests of Arrays Similar to that Involved.** Where an actual calorific test of the specific array under consideration cannot be found, it may be possible to find data on one or more tests that are similar to the fuel of concern in important matters such as type of fuel, arrangement, or ignition scenario. The more the actual tests are similar to the fuel of concern, the higher the confidence that can be placed in the derived rate of heat release. The addition of engineering judgment, however, might be needed to adjust the test data to that approximating the fuel of concern. If rate of heat release has not been directly measured, it can be estimated using the method described for estimating burning rate from flame height in Section B.3.

**B.5 Algorithms Derived from Tests of Arrays Having Similar Fuels and Dimensional Characteristics.**

**B.5.1 Pool Fires.** In many cases, the rate of heat release of a tested array has been divided by a common dimension, such as occupied floor area, to derive a normalized rate of heat release per unit area. The rate of heat release of pool fires is the best documented and accepted algorithm in this class.

An equation for the mass release rate from a pool fire is as follows [76]:

$$m'' = m''_o(1 - e^{-kBD}) \qquad \text{(B.3)}$$

The variables for Equation (B.3) are as shown in Table B.5.1 [76].

**Table B.5.1 Data for Large Pool Burning Rate Estimates**

| Material | Density (lb/ft$^3$) | $h_c$ (Btu/lb) | $m''_o$ (lb/ft$^2$·s) | $kB$ (ft$^{-1}$) |
|---|---|---|---|---|
| Cryogenics* | | | | |
| Liquid $H_2$ | 4.4 | 55,500 | 0.0035 | 1.9 |
| LNG (mostly $CH_4$) | 26 | 21,500 | 0.016 | 0.33 |
| LPG (mostly $C_3H_8$) | 37 | 20,000 | 0.02 | 0.43 |
| Alcohols | | | | |
| Methanol ($CH_3OH$) | 50 | 8,500 | 0.0035 | |
| Ethanol ($C_2H_5OH$) | 50 | 11,500 | 0.0031 | † |
| Simple organic fuels | | | | † |
| Butane ($C_4H_{10}$) | 36 | 20,000 | 0.016 | 0.82 |
| Benzene ($C_5H_6$) | 53 | 17,000 | 0.017 | 0.82 |
| Hexane ($C_6H_{14}$) | 41 | 19,000 | 0.015 | 0.58 |
| Heptane ($C_7H_{16}$) | 42 | 19,000 | 0.021 | 0.34 |
| Xylene ($C_8H_{10}$) | 54 | 17,500 | 0.018 | 0.42 |
| Acetone ($C_3H_6O$) | 49 | 11,000 | 0.0084 | 0.58 |
| Dioxane ($C_4H_8O_2$) | 65 | 11,000 | 0.0037** | 1.6** |
| Diethyl ether ($C_4H_{10}O$) | 45 | 14,500 | 0.017 | 0.21 |
| Petroleum products | | | | |
| Benzene | 46 | 19,000 | 0.0098 | 1.1 |
| Gasoline | 46 | 19,000 | 0.011 | 0.64 |
| Kerosene | 51 | 18,500 | 0.008 | 1.1 |
| JP-4 | 47 | 18,500 | 0.01 | 1.1 |
| JP-5 | 51 | 18,500 | 0.011 | 0.49 |
| Transformer oil, hydrocarbon | 47 | 20,000 | 0.008** | 0.21** |
| Fuel oil, heavy | 59–62 | 17,000 | 0.0072 | 0.52 |
| Crude oil | 52–55 | 18,000 | 0.0045–0.0092 | 0.85 |
| Solids | | | | |
| Polymethylmethacrylate ($C_5H_8O_2$)$_n$ | 74 | 10,000 | 0.0041 | 1.0 |
| Polypropylene ($C_3H_6$)$_n$ | 56 | 18,500 | 0.0037 | |
| Polystyrene ($C_8H_8$)$_n$ | 66 | 17,000 | 0.007 | |

*For pools on dry land, not over water.
**Estimate uncertain, since only two data points available.
† — Value independent of diameter in turbulent regime.

The mass rates derived from Equation (B.3) are converted to rates of heat release using Equation (B.1) and the heat of combustion from Table B.5.1. The rate of heat release per unit area times the area of the pool yields heat release data for the anticipated fire.

**B.5.2 Other Normalized Data.** Other data based on burning rate per unit area in tests have been developed. Tables B.5.2(a) and B.5.2(b) list the most available of these data.

**Table B.5.2(a) Unit Heat Release Rate for Commodities**

| Commodity | Btu/sec·ft$^2$ of Floor Area |
|---|---|
| Wood pallets, stacked $1^1/_2$ ft high (6–12% moisture) | 125 |
| Wood pallets, stacked 5 ft high (6–12% moisture) | 350 |
| Wood pallets, stacked 10 ft high (6–12% moisture) | 600 |
| Wood pallets, stacked 16 ft high (6–12% moisture) | 900 |
| Mail bags, filled, stored 5 ft high | 35 |
| Cartons, compartmented, stacked 15 ft high | 150 |
| PE letter trays, filled, stacked 5 ft high on cart | 750 |
| PE trash barrels in cartons, stacked 15 ft high | 175 |
| PE fiberglass shower stalls in cartons, stacked 15 ft high | 125 |
| PE bottles packed in compartmented cartons | 550 |
| PE bottles in cartons, stacked 15 ft high | 175 |
| PU insulation board, rigid foam, stacked 15 ft high | 170 |
| PS jars packed in compartmented cartons | 1250 |
| PS tubs nested in cartons, stacked 14 ft high | 475 |
| PS toy parts in cartons, stacked 15 ft high | 180 |
| PS insulation board, rigid foam, stacked 14 ft high | 290 |
| PVC bottles packed in compartmented cartons | 300 |
| PP tubs packed in compartmented cartons | 390 |
| PP & PE film in rolls, stacked 14 ft high | 550 |
| Methyl alcohol | 65 |
| Gasoline | 290 |
| Kerosene | 290 |
| Diesel oil | 175 |

Note: Heat release rate per unit floor area of fully involved combustibles, based on negligible radiative feedback from the surroundings and 100 percent combustion efficiency.
PE = Polyethylene
PP = Polypropylene
PS = Polystyrene
PU = Polyurethane
PV = Polyvinyl chloride

**Table B.5.2(b) Maximum Heat Release Rates**

| Warehouse Materials | Growth Time (sec) | Heat Release Density ($q$) | Classification (s—slow) (m—medium) (f—fast) |
|---|---|---|---|
| Wood pallets, stacked $1^1/_2$ ft high (6–12% moisture) | 150–310 | 110 | m–f |
| Wood pallets, stacked 5 ft high (6–12% moisture) | 90–190 | 330 | f |
| Wood pallets, stacked 10 ft high (6–12% moisture) | 80–110 | 600 | f |
| Wood pallets, stacked 16 ft high (6–12% moisture) | 75–105 | 900 | f |
| Mail bags, filled, stored 5 ft high | 190 | 35 | f |
| Cartons, compartmented, stacked 15 ft high | 60 | 200 | * |
| Paper, vertical rolls, stacked 20 ft high | 15–28 | — | * |
| Cotton (also PE, PE/Cot, Acrylic/Nylon/PE), garments in 12-ft high rack | 20–42 | — | * |
| Cartons on pallets, rack storage, 15–30 ft high | 40–280 | — | m–f |
| Paper products, densely packed in cartons, rack storage, 20 ft high | 470 | — | m–s |
| PE letter trays, filled, stacked 5 ft high on cart | 190 | 750 | f |
| PE trash barrels in cartons stacked 15 ft high | 55 | 250 | * |
| FRP shower stalls in cartons, stacked 15 ft high | 85 | 110 | * |
| PE bottles packed in compartmented cartons | 85 | 550 | * |
| PE bottles in cartons, stacked 15 ft high | 75 | 170 | * |
| PE pallets, stacked 3 ft high | 130 | — | f |
| PE pallets, stacked 6–8 ft high | 30–55 | — | * |
| PU mattress, single, horizontal | 110 | — | f |
| PF insulation, board, rigid foam, stacked 15 ft high | 8 | 170 | * |
| PS jars packed in compartmented cartons | 55 | 1200 | * |
| PS tubs nested in cartons, stacked 14 ft high | 105 | 450 | f |

**Table B.5.2(b) Maximum Heat Release Rates** *(Continued)*

| Warehouse Materials | Growth Time (sec) | Heat Release Density ($q$) | Classification (s—slow) (m—medium) (f—fast) |
|---|---|---|---|
| PS toy parts in cartons, stacked 15 ft high | 110 | 180 | f |
| PS insulation board, rigid, stacked 14 ft high | 7 | 290 | * |
| PVC bottles packed in compartmented cartons | 9 | 300 | * |
| PP tubs packed in compartmented cartons | 10 | 390 | * |
| PP and PE film in rolls, stacked 14 ft high | 40 | 350 | * |
| Distilled spirits in barrels, stacked 20 ft high | 23–40 | — | * |
| Methyl alcohol | — | 65 | — |
| Gasoline | — | 200 | — |
| Kerosene | — | 200 | — |
| Diesel oil | — | 180 | — |

For SI units, 1 ft = 0.305 m.
Notes:
1. $Qm = qA$

where:
$Qm$ = maximum heat release rate (Btu/sec)
$q$ = heat release density (Btu/sec·ft$^2$)
$A$ = floor area (ft$^2$)

2. The heat release rates per unit floor area are for fully involved combustibles, assuming 100 percent efficiency. The growth times shown are those required to exceed 1000 Btu/sec heat release rate for developing fires assuming 100 percent combustion efficiency.
(PE = polyethylene; PS = polystyrene; PVC = polyvinyl chloride; PP = polypropylene; PU = polyurethane; FRP = fiberglass-reinforced polyester.)
*Fire growth rate exceeds classification criteria.

**B.5.3 Other Useful Data.** Other data that are not normalized might be useful in developing the rate of heat release curve. Examples are included in Tables B.5.3(a) through B.5.3(h).

**Table B.5.3(a) Maximum Heat Release Rates from Fire Detection Institute Analysis**

| Commodity | Approximate Values (Btu/sec) |
|---|---|
| Medium wastebasket with milk cartons | 100 |
| Large barrel with milk cartons | 140 |
| Upholstered chair with polyurethane foam | 350 |
| Latex foam mattress (heat at room door) | 1200 |
| Furnished living room (heat at open door) | 4000–8000 |

**Table B.5.3(b) Characteristics of Ignition Sources [3]**

| Ignition Source | Typical Heat Output (W) | Burn Time[a] (sec) | Maximum Flame Height (mm) | Flame Width (mm) | Maximum Heat Flux (kW/m$^2$) |
|---|---|---|---|---|---|
| Cigarette 1.1 g (not puffed, laid on solid surface), bone dry | | | | | |
| Conditioned to 50% | 5 | 1,200 | — | — | 42 |
| Relative humidity | 5 | 1,200 | — | — | 35 |
| Methenamine pill, 0.15 g | 45 | 90 | — | — | 4 |
| Match, wooden (laid on solid surface) | 80 | 20–30 | 30 | 14 | 18–20 |
| Wood cribs, BS 5852 | | | | | |
| Part 2 | | | | | |
| No. 4 crib, 8.5 g | 1,000 | 190 | | | 15[d] |
| No. 5 crib, 17 g | 1,900 | 200 | | | 17[d] |
| No. 6 crib, 60 g | 2,600 | 190 | | | 20[d] |
| No. 7 crib, 126 g | 6,400 | 350 | | | 25[d] |
| Crumpled brown lunch bag, 6 g | 1,200 | 80 | | | |
| Crumpled wax paper, 4.5 g (tight) | 1,800 | 25 | | | |
| Crumpled wax paper, 4.5 g (loose) | 5,300 | 20 | | | |
| Folded double-sheet newspaper, 22 g (bottom ignition) | 4,000 | 100 | | | |
| Crumpled double-sheet newspaper, 22 g (top ignition) | 7,400 | 40 | | | |
| Crumpled double-sheet newspaper, 22 g (bottom ignition) | 17,000 | 20 | | | |
| Polyethylene wastebasket, 285 g, filled with 12 milk cartons (390 g) | 50,000 | 200[b] | 550 | 200 | 35[c] |
| Plastic trash bags, filled with cellulosic trash (1.2–14 kg)[e] | 120,000 to 350,000 | 200[b] | | | |

For SI units, 1 in. = 25.4 mm; 1 Btu/sec = 1.055 W; 1 oz = 0.02835 kg = 28.35 g; 1 Btu/ft$^2$-sec = 11.35 kW/m$^2$.
[a]Time duration of significant flaming.
[b]Total burn time in excess of 1800 seconds.
[c]As measured on simulation burner.
[d]Measured from 25 mm away.
[e]Results vary greatly with packing density.

**Table B.5.3(c) Characteristics of Typical Furnishings as Ignition Sources [3]**

| | Total Mass (kg) | Total Heat Content (MJ) | Maximum Rate of Heat Release (kW) | Maximum Thermal Radiation to Center of Floor[a] (kW/m$^2$) |
|---|---|---|---|---|
| Waste paper baskets | 0.73–1.04 | 0.7–7.3 | 4–18 | 0.1 |
| Curtains, velvet, cotton | 1.9 | 24 | 160–240 | 1.3–3.4 |
| Curtains, acrylic/cotton | 1.4 | 15–16 | 130–150 | 0.9–1.2 |
| TV sets | 27–33 | 145–150 | 120–290 | 0.3–2.6 |
| Chair mockup | 1.36 | 21–22 | 63–66 | 0.4–0.5 |
| Sofa mockup | 2.8 | 42 | 130 | 0.9 |
| Arm chair | 26 | 18 | 160 | 1.2 |
| Christmas trees, dry | 6.5–7.4 | 11–41 | 500–650 | 3.4–14 |

For SI units, 1 lb = 0.4536 kg = 453.6 g; 1 Btu = $1.055 \times 10^{-3}$ MJ; 1 Btu/sec = 1.055 kW; 1 Btu/ft$^2$-sec = 11.35 kW/m$^2$
[a]Measured at approximately 2 m away from the burning object.

**Table B.5.3(d) Heat Release Rates of Chairs in Recent NBS Tests [3]**

| Specimen | (kg) | Mass Combustible (kg) | Style | Frame | Padding | Fabric | Interliner | Peak *m* (g/sec) | Peak *q* (kW) |
|---|---|---|---|---|---|---|---|---|---|
| C12 | 17.9 | 17.0 | Traditional easy chair | Wood | Cotton | Nylon | — | 19.0 | 290[a] |
| F22 | 31.9 | | Traditional easy chair | Wood | Cotton (FR) | Cotton | — | 25.0 | 370 |
| F23 | 31.2 | | Traditional easy chair | Wood | Cotton (FR) | Olefin | — | 42.0 | 700 |
| F27 | 29.0 | | Traditional easy chair | Wood | Mixed | Cotton | — | 58.0 | 920 |
| F28 | 29.2 | | Traditional easy chair | Wood | Mixed | Cotton | — | 42.0 | 730 |
| CO2 | 13.1 | 12.2 | Traditional easy chair | Wood | Cotton, PU | Olefin | — | 13.2 | 800[b] |
| CO3 | 13.6 | 12.7 | Traditional easy chair | Wood | Cotton, PU | Cotton | — | 17.5 | 460[a] |
| CO1 | 12.6 | 11.7 | Traditional easy chair | Wood | Cotton, PU | Cotton | — | 17.5 | 260[a] |
| CO4 | 12.2 | 11.3 | Traditional easy chair | Wood | PU | Nylon | — | 75.7 | 1350[b] |
| C16 | 19.1 | 18.2 | Traditional easy chair | Wood | PU | Nylon | Neoprene | NA | 180 |
| F25 | 27.8 | | Traditional easy chair | Wood | PU | Olefin | — | 80.0 | 1990 |
| T66 | 23.0 | | Traditional easy chair | Wood | PU, polyester | Cotton | — | 27.7 | 640 |
| F21 | 28.3 | | Traditional easy chair | Wood | PU (FR) | Olefin | — | 83.0 | 1970 |
| F24 | 28.3 | | Traditional easy chair | Wood | PU (FR) | Cotton | — | 46.0 | 700 |
| C13 | 19.1 | 18.2 | Traditional easy chair | Wood | PU | Nylon | Neoprene | 15.0 | 230[a] |
| C14 | 21.8 | 20.9 | Traditional easy chair | Wood | PU | Olefin | Neoprene | 13.7 | 220[a] |
| C15 | 21.8 | 20.9 | Traditional easy chair | Wood | PU | Olefin | Neoprene | 13.1 | 210[b] |
| T49 | 15.7 | | Easy chair | Wood | PU | Cotton | — | 14.3 | 210 |
| F26 | 19.2 | | Thinner easy chair | Wood | PU (FR) | Olefin | — | 61.0 | 810 |
| F33 | 39.2 | | Traditional loveseat | Wood | mixed | Cotton | — | 75.0 | 940 |
| F31 | 40.0 | | Traditional loveseat | Wood | PU (FR) | Olefin | — | 130.0 | 2890 |
| F32 | 51.5 | | Traditional sofa | Wood | PU (FR) | Olefin | — | 145.0 | 3120 |
| T57 | 54.6 | | Loveseat | Wood | PU, cotton | PVC | — | 61.9 | 1100 |
| T56 | 11.2 | | Office chair | Wood | latex | PVC | — | 3.1 | 80 |
| CO9/T64 | 16.6 | 16.2 | Foam block chair | Wood (part) | PU, polyester | PU | — | 19.9 | 460 |
| CO7/T48 | 11.4 | 11.2 | Modern easy chair | PS foam | PU | PU | — | 38.0 | 960 |
| C10 | 12.1 | 8.6 | Pedestal chair | Rigid PU foam | PU | PU | — | 15.2 | 240[a] |

**Table B.5.3(d) Heat Release Rates of Chairs in Recent NBS Tests [3] *(Continued)***

| Specimen | (kg) | Mass Combustible (kg) | Style | Frame | Padding | Fabric | Interliner | Peak *m* (g/sec) | Peak *q* (kW) |
|---|---|---|---|---|---|---|---|---|---|
| C11 | 14.3 | 14.3 | Foam block chair | — | PU | Nylon | — | NA | 810[b] |
| F29 | 14.0 | | Traditional easy chair | PP foam | PU | Olefin | — | 72.0 | 1950 |
| F30 | 25.2 | | Traditional easy chair | Rigid PU foam | PU | Olefin | — | 41.0 | 1060 |
| CO8 | 16.3 | 15.4 | Pedestal swivel chair | Molded PE | PU | PVC | — | 112.0 | 830[b] |
| CO5 | 7.3 | 7.3 | Bean bag chair | — | Polystyrene | PVC | — | 22.2 | 370[a] |
| CO6 | 20.4 | 20.4 | Frameless foam back chair | — | PU | Acrylic | — | 151.0 | 2480[b] |
| T50 | 16.5 | | Waiting room chair | Metal | Cotton | PVC | — | NA | <10 |
| T53 | 15.5 | 1.9 | Waiting room chair | Metal | PU | PVC | — | 13.1 | 270 |
| T54 | 27.3 | 5.8 | Metal frame loveseat | Metal | PU | PVC | — | 19.9 | 370 |
| T75/F20 | 7.5(×4) | 2.6 | Stacking chairs (4) | Metal | PU | PVC | — | 7.2 | 160 |

For SI units, 1 lb/sec = 0.4536 kg/sec = 453.6 g/sec
1 lb = 0.4536 kg
1 Btu/sec = 1.055 kW
[a]Estimated from mass loss records and assumed $Wh_c$.
[b]Estimated from doorway gas concentrations.

**Table B.5.3(e) Effect of Fabric Type on Heat Release Rate in Table B.5.3(a) (within each group all other construction features were kept constant) [3]**

| Specimen | Full-Scale Peak *q* (kW) | Padding | Fabric |
|---|---|---|---|
| | Group 1 | | |
| F24 | 700 | Cotton (750 g/m$^2$) | FR PU foam |
| F21 | 1970 | Polyolefin (560 g/m$^2$) | FR PU foam |
| | Group 2 | | |
| F22 | 370 | Cotton (750 g/m$^2$) | Cotton batting |
| F23 | 700 | Polyolefin (560 g/m$^2$) | Cotton batting |
| | Group 3 | | |
| 28 | 760 | None | FR PU foam |
| 17 | 530 | Cotton (650 g/m$^2$) | FR PU foam |
| 21 | 900 | Cotton (110 g/m$^2$) | FR PU foam |
| 14 | 1020 | Polyolefin (650 g/m$^2$) | FR PU foam |
| 7, 19 | 1340 | Polyolefin (360 g/m$^2$) | FR PU foam |

For SI units, 1 lb/ft$^2$ = 48.83 g/m$^2$
1 oz/ft$^2$ = 305 g/m$^2$
1 Btu/sec = 1.055 kW

**Table B.5.3(f) Effect of Padding Type on Maximum Heat Release Rate in Table B.5.3(d) (within each group all other construction features were kept constant) [3]**

| Specimen | Full-Scale Peak *q* (kW) | Padding | Fabric |
|---|---|---|---|
| | Group 1 | | |
| F21 | 1970 | FR PU foam | Polyolefin (560 g/m$^2$) |
| F23 | 1990 | NFR PU foam | Polyolefin (560 g/m$^2$) |
| | Group 2 | | |
| F21 | 1970 | FR PU foam | Polyolefin (560 g/m$^2$) |
| F23 | 700 | Cotton batting | Polyolefin (560 g/m$^2$) |
| | Group 3 | | |
| F24 | 700 | FR PU foam | Cotton (750 g/m$^2$) |
| F22 | 370 | Cotton batting | Cotton (750 g/m$^2$) |
| | Group 4 | | |
| 12, 27 | 1460 | NFR PU foam | Polyolefin (360 g/m$^2$) |
| 7, 19 | 1340 | FR PU foam | Polyolefin (360 g/m$^2$) |
| 15 | 120 | Neoprene foam | Polyolefin (360 g/m$^2$) |
| | Group 5 | | |
| 20 | 430 | NFR PU foam | Cotton (650 g/m$^2$) |
| 17 | 530 | FR PU foam | Cotton (650 g/m$^2$) |
| 22 | 0 | Neoprene foam | Cotton (650 g/m$^2$) |

For SI units, 1 lb/ft$^2$ = 48.83 g/m$^2$
1 oz/ft$^2$ = 305 g/m$^2$
1 Btu/sec = 1.055 kW

**Table B.5.3(g) Effect of Frame Material for Specimens with NFR PU Padding and Polyolefin Fabrics [3]**

| Specimen | Mass (kg) | Peak *q* (kW) | Frame |
|---|---|---|---|
| F25 | 27.8 | 1990 | Wood |
| F30 | 25.2 | 1060 | Polyurethane |
| F29 | 14.0 | 1950 | Polypropylene |

For SI units, 1 lb = 0.4536 kg
1 Btu/sec = 1.055 kW

**Table B.5.3(h) Considerations for Selecting Heat Release Rates for Design**

| | | |
|---|---|---|
| **Constant Heat Release Rate Fires** | | |
| Theobald (industrial) | 260 kW/$m^2$ | (approx. 26 Btu/sec-$ft^2$) |
| Law [16] (offices) | 290 kW/$m^2$ | (approx. 29 Btu/sec-$ft^2$) |
| Hansell & Morgan [67] (hotel rooms) | 249 kW/$m^2$ | (approx. 25 Btu/sec-$ft^2$) |
| **Variable Heat Release Rate Fires** | | |
| **NBSIR 88-3695 Fuel Configuration** | **Fire Growth Rate** | |
| Computer workstation | | |
| Free burn | Slow–fast | |
| Compartment | Very slow | |
| Shelf storage | | |
| Free burn | Medium up to 200 sec, fast after 200 sec | |
| Office module | Very slow–medium | |
| **NISTIR 483 Fuel Commodity** | **Peak Heat Release Rate (kW)** | |
| Computer workstation | 1000–1300 | |
| **NBS Monograph 173 Fuel Commodity** | **Peak Heat Release (kW)** | |
| Chairs | 80–2480 (<10, metal frame) | |
| Loveseats | 940–2890 (370, metal frame) | |
| Sofa | 3120 | |

**B.6 Calculated Fire Description Based on Tested Properties.**

**B.6.1 Background.** It is possible to make general estimates of the rate of heat release of burning materials based on the fire properties of that material. The fire properties involved can be determined by small-scale tests. The most important of these tests are calorimeter tests involving both oxygen depletion calorimetry and the application of external heat flux to the sample while determining time to ignition, rate of mass release, and rate of heat release for the specific applied flux. Most prominent of the current test apparatus are the cone calorimeter (ASTM E 1354, *Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*) and the Factory Mutual calorimeter [80]. In addition to these directly measured properties, it is possible to derive ignition temperature, critical ignition flux, effective thermal inertia ($k\rho c$), heat of combustion, and heat of gasification based on results from these calorimeters. Properties not derivable from these calorimeters and essential to determining flame spread in directions not concurrent with the flow of the flame can be obtained from the LIFT (lateral ignition and flame travel) apparatus *(see ASTM E 1321, Standard Test Method for Determining Material Ignition and Flame Spread Properties)*. This section presents a concept of the use of fire property test data as the basis of an analytical evaluation of the rate of heat release involved in the use of a tested material. The approach outlined in this section is based on that presented by Nelson and Forssell [81].

**B.6.2 Discussion of Measured Properties.** Table B.6.2 lists the type of fire properties obtainable from the cone or Factory Mutual calorimeters and similar instruments.

**Table B.6.2 Relation of Calorimeter-Measured Properties to Fire Analysis**

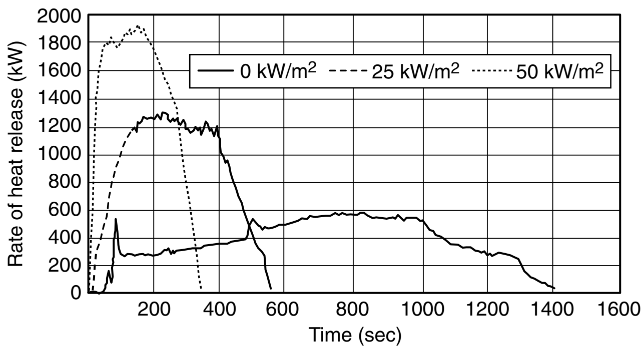
| Property | Ignition | Flame Spread | Fire Size (Energy) |
|---|---|---|---|
| Rate of heat release* | | xxx | xxx |
| Mass loss* | | | xxx |
| Time to ignition* | xxx | xxx | |
| Effective thermal properties† | xxx | xxx | |
| Heat of combustion† | | xxx | xxx |
| Heat of gasification† | | | xxx |
| Critical ignition flux† | xxx | xxx | |
| Ignition temp.† | xxx | xxx | |

* Property is a function of the externally applied incident flux.
†Derived properties from calorimeter measurements.

In Table B.6.2, the rate of heat release (RHR), mass loss, and time to ignition are functions of the externally applied incident radiant heat flux imposed on the tested sample. The purpose of the externally applied flux is to simulate the fire environment surrounding a burning item. In general, it can be estimated that a free-burning fuel package (i.e., one that burns in the open and is not affected by energy feedback from a hot gas layer of a heat source other than its own flame) is impacted by a flux in the range of 25 kW/$m^2$ to 50 kW/$m^2$. If the fire is in a space and conditions are approaching flashover, this can increase to the range of 50 kW/$m^2$ to 75 kW/$m^2$. In fully developed, post-flashover fires, a range of 75 kW/$m^2$ to over 100 kW/$m^2$ can be expected. The following is a discussion of the individual properties measured or derived and the usual form used to report the property.

(a) *Rate of Heat Release.* Rate of heat release is determined by oxygen depletion calorimetry. Each test is run at a user-specific incident flux and either for a predetermined period of time or until the sample is consumed. The complete results are presented in the form of a plot of rate of heat release against time, with the level of applied flux noted. In some cases, the rate of heat release for several tests of the same material at different levels of applied flux is plotted on a single curve for comparison. Figure B.6.2(a) is an example of such a plotting.

**FIGURE B.6.2(a) Typical graphic output of cone calorimeter test.**




Often only the peak rate of heat release at a specific flux is reported. Table B.6.2(a) is an example.

**Table B.6.2(a) Average Maximum Heat Release Rates (kW/m²)**

| Material | Orientation | 2.2 Btu/sec/ft² Exposing Flux | 4.4 Btu/sec/ft² Exposing Flux | 6.6 Btu/sec/ft² Exposing Flux |
|---|---|---|---|---|
| PMMA | Horizontal | 57 | 79 | 114 |
| | Vertical | 49 | 63 | 114 |
| Pine | Horizontal | 12 | 21 | 23 |
| | Vertical | 11 | 15 | 56 |
| Sample A | Horizontal | 11 | 18 | 22 |
| | Vertical | 8 | 11 | 19 |
| Sample B | Horizontal | 12 | 15 | 21 |
| | Vertical | 5.3 | 18 | 29 |
| Sample C | Horizontal | | 19 | 22 |
| | Vertical | | 15 | 15 |
| Sample D | Horizontal | 6.2 | 13 | 13 |
| | Vertical | | 11 | 11 |

(b) *Mass Loss Rate (m).* Mass loss rate is determined by a load cell. The method of reporting is identical to that for rate of heat release. In the typical situation where the material has a consistent heat of combustion, the curves for mass loss rate and rate of heat release are similar in shape.

(c) *Time to Ignition ($q_i$).* Time to ignition is reported for each individual test and applied flux level conducted.

(d) *Effective Thermal Inertia (kDc).* Effective thermal inertia is a measurement of the heat rise response of the tested material to the heat flux imposed on the sample. It is derived at the time of ignition and is based on the ratio of the actual incident flux to the critical ignition flux and the time to ignition. A series of tests at different levels of applied flux is necessary to derive the effective thermal inertia. Effective thermal inertia derived in this manner can differ from and be preferable to that derived using handbook data for the values of *k*, *D*, and *c* derived without a fire.

(e) *Heat of Combustion ($H_c$).* Heat of combustion is derived by dividing the measured rate of heat release by the measured mass loss rate. It is normally reported as a single value, unless the sample is a composite material and the rates of heat release and mass loss vary significantly with time and exposure.

(f) *Heat of Gasification ($h_g$).* Heat of gasification is the flux needed to pyrolyze a unit mass of fuel. It is derived as a heat balance and is usually reported as a single value in terms of the amount of energy per unit mass of material released (e.g., kJ/g).

(g) *Critical Ignition Flux ($q_{cr}$).* Critical ignition flux is the minimum level of incident flux on the sample needed to ignite the sample, given an unlimited time of application. At incident flux levels less than the critical ignition flux, ignition does not take place.

(h) *Ignition Temperature ($T_i$).* Ignition temperature is the surface temperature of a sample at which flame occurs. This is a sample material value that is independent of the incident flux. It is derivable from the calorimeter tests, the LIFT apparatus test, and other tests. It is derived from the time to ignite in a given test, the applied flux in that test, and the effective thermal inertia of the sample. It is reported at a single temperature. If the test includes a pilot flame or spark, the reported temperature is for piloted ignition; if there is no pilot present, the temperature is for autoignition. Most available data are for piloted ignition.

**B.6.3 Ignition.** Equations for time to ignition, $t_{ig}$, are given for both thermally thin and thermally thick materials, as defined in B.6.3(a) and (b). For materials of intermediate depth, estimates for $t_{ig}$ necessitate considerations beyond the scope of this presentation [40, 77].

(a) *Thermally Thin Materials.* Relative to ignition from a constant incident heat flux, $q_i$, at the exposed surface and with relatively small heat transfer losses at the unexposed surface, a thermally thin material is a material whose temperature is relatively uniform throughout its entire thickness, $l$, at $t = t_{ig}$. For example, at $t = t_{ig}$,

$$T_{exposed} - T_{unexposed} = T_{ig} - T_{unexposed} < 0.1(T_{ig} - T_o) \quad \text{(B.4)}$$

Equation (B.4) can be used to show that a material is thermally thin [77] if

$$1 < 0.6(t_{ig}'')^{1/2} \quad \text{(B.5)}$$

For example, for sheets of maple or oak wood (where the thermal diffusivity $\alpha = 1.28 \times 10^{-7}$ m²/sec [78]), if $t_{ig} = 35$ seconds is measured in a piloted ignition test, then, according to Equation (B.5), if the sample thickness is less than approximately 0.0013 m, the unexposed surface of the sample can be expected to be relatively close to $T_{ig}$ at the time of ignition, and the sample is considered to be thermally thin.

The time to ignition of a thermally thin material subjected to incident flux above a critical incident flux is

$$t_{ig} = \rho c l \frac{(T_{ig} - T_o)}{\dot{q}''_i} \qquad \text{(B.6)}$$

(b) *Thermally Thick Materials.* Relative to the type of ignition test described in B.6.3(a), a sample of a material of a thickness, *l*, is considered to be thermally thick if the increase in temperature of the unexposed surface is relatively small compared to that of the exposed surface at $t = t_{ig}$. For example, at $t = t_{ig}$,

$$T_{unexposed} B T_o < 0.1(T_{exposed} B T_o) = 0.1(T_{ig} B T_o) \qquad \text{(B.7)}$$

Equation (B.7) can be used to show that a material is thermally thick [77] if

$$l > 2(t_{ig} 10)^{1/2} \qquad \text{(B.8)}$$

For example, according to Equation (B.8), in the case of an ignition test on a sheet of maple or oak wood, if $t_{ig}$ = 35 seconds is measured in a piloted ignition test, then, if the sample thickness is greater than approximately 0.0042 m, the unexposed surface of the sample can be expected to be relatively close to $T_o$ at $t = t_{ig}$ and the sample is considered to be thermally thick.

Time to ignition of a thermally thick material subjected to incident flux above a critical incident flux is

$$t_{ig} = \left(\frac{B}{4}\right) k \rho c \left(\frac{T_{ig} B T_o}{q''_i}\right)^2 \qquad \text{(B.9)}$$

It should be noted that a particular material is not intrinsically thermally thin or thick (i.e., the characteristic of being thermally thin or thick is not a material characteristic or property) but also depends on the thickness of the particular sample (i.e., a particular material can be implemented in either a thermally thick or thermally thin configuration).

(c) *Propagation Between Separate Fuel Packages.* Where the concern is for propagation between individual separated fuel packages, incident flux can be calculated using traditional radiation heat transfer procedures [79].

The rate of radiation heat transfer from a flaming fuel package of total energy release rate, *Q*, to a facing surface element of an exposed fuel package can be estimated from

$$q_{inc}'' = \frac{X_r Q}{4 \pi r^2} \qquad \text{(B.10)}$$

where:

$q_{inc}''$ = incident flux on exposed fuel
$X_r$ = radiant fraction of exposing fire
$Q$ = rate of heat release of exposing fire
$r$ = radial distance from center of exposing fire to exposed fuel

**B.6.4 Estimating Rate of Heat Release.** As discussed in B.6.2, tests have demonstrated that the energy feedback from a burning fuel package ranges from approximately 25 kW/m$^2$ to 50 kW/m$^2$. For a reasonable conservative analysis, it is recommended that test data developed with an incident flux of 50 kW/m$^2$ be used. For a first-order approximation, it should be assumed that all of the surfaces that can be simultaneously involved in burning are releasing energy at a rate equal to that determined by testing the material in a fire properties calorimeter with an incident flux of 50 kW/m$^2$ for a free-burning material and 75 kW/m$^2$ to 100 kW/m$^2$ for post-flashover conditions.

In making this estimate, it is necessary to assume that all surfaces that can "see" an exposing flame (or superheated gas, in the post-flashover condition) are burning and releasing energy and mass at the tested rate. If sufficient air is present, the rate of heat release estimate is then calculated as the product of the exposed area and the rate of heat release per unit area as determined in the test calorimeter. Where there are test data taken at the incident flux of the exposing flame, the tested rate of heat release should be used. Where the test data are for a different incident flux, the burning rate should be estimated using the heat of gasification as expressed in Equation (B.11) to calculate the mass burning rate per unit area:

$$\dot{m}'' = \frac{\dot{q}''_i}{h_c} \qquad \text{(B.11)}$$

The resulting mass loss rate is then multiplied by the derived effective heat of combustion and the burning area exposed to the incident flux to produce the estimated rate of heat release as follows:

$$\dot{Q}_i'' = \dot{m}'' h_c A \qquad \text{(B.12)}$$

**B.6.5 Flame Spread.** If it is desired to predict the growth of fire as it propagates over combustible surfaces, it is necessary to estimate flame spread. The computation of flame spread rates is an emerging technology still in an embryonic stage. Predictions should be considered as order-of-magnitude estimates.

Flame spread is the movement of the flame front across the surface of a material that is burning (or exposed to an ignition flame) where the exposed surface is not yet fully involved. Physically, flame spread can be treated as a succession of ignitions resulting from the heat energy produced by the burning portion of a material, its flame, and any other incident heat energy imposed upon the unburned surface. Other sources of incident energy include another burning object, high-temperature gases that can accumulate in the upper portion of an enclosed space, and the radiant heat sources used in a test apparatus such as the cone calorimeter or the LIFT mechanism. For analysis purposes, flame spread can be divided into two categories, that which moves in the same direction as the flame (concurrent or wind-aided flame spread) and that which moves in any other direction (lateral or opposed flame spread). Concurrent flame spread is assisted by the incident heat flux from the flame to unignited portions of the burning material. Lateral flame spread is not so assisted and tends to be much slower in progression unless an external source of heat flux is present. Concurrent flame spread can be expressed as follows:

$$V = \frac{\dot{q}_i'' L}{k\rho c(T_{ig} - T_s)^2} \quad \text{(B.13)}$$

The values for $k\rho c$ and ignition temperature are calculated from the cone calorimeter as previously discussed. For this equation, the flame length ($L$) is measured from the leading edge of the burning region.

## Appendix C *t*-Squared Fires

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

**C.1** Over the past decade, persons interested in developing generic descriptions of the rate of heat release of accidental open flaming fires have used a "*t*-squared" approximation for this purpose. A *t*-squared fire is one where the burning rate varies proportionally to the square of time. Frequently, *t*-squared fires are classed by speed of growth, labeled fast, medium, and slow (and occasionally ultra-fast). Where these classes are used, they are defined on the basis of the time required for the fire to grow to a rate of heat release of 1000 Btu/sec. The times related to each of these classes are as follow:

| Class | Time to Reach 1000 Btu/sec |
|---|---|
| Ultra-fast | 75 sec |
| Fast | 150 sec |
| Medium | 300 sec |
| Slow | 600 sec |

The general equation is:

$$q = at^2$$

where:

$q$ = rate of heat release (normally in Btu/sec or kW)
$a$ = a constant governing the speed of growth
$t$ = time (normally in sec)

**C.2 Relevance of *t*-Squared Approximation to Real Fires.** A *t*-squared fire can be viewed as one where the rate of heat release per unit area is constant over the entire ignited surface and the fire is spreading as a circle with a steadily increasing radius. In such cases, the burning area increases as the square of the steadily increasing fire radius. Of course, other fires that do not have such a conveniently regular fuel array and consistent burning rate might or might not actually produce a *t*-squared curve. The tacit assumption is that the *t*-squared approximation is close enough for reasonable design decisions.

Figure C.2(a) is abstracted from NFPA 204, *Guide for Smoke and Heat Venting*. It is presented to demonstrate that most fires have an incubation period where the fire does not conform to a *t*-squared approximation. In some cases this incubation period can be a serious detriment to the use of the *t*-squared approximation. In most instances this is not a serious concern in the atria and other large spaces covered by this guide. It is expected that the rate of heat release during the incubation period would not usually be sufficient to cause activation of the smoke detection system. In any case where such activation happens or human observation results in earlier activation of the smoke management system, a fortuitous safeguard would result.

**FIGURE C.2(a) Conceptual illustration of continuous fire growth.**

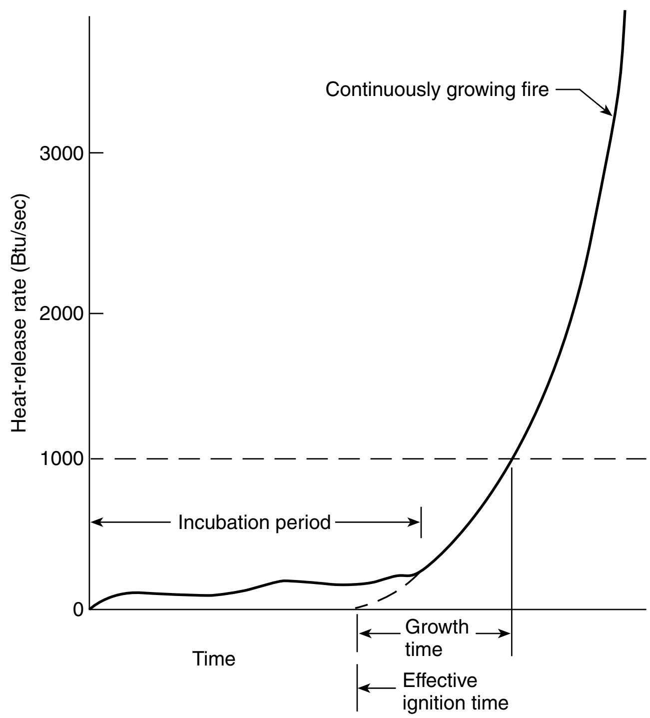



Figure C.2(b), extracted from Nelson [2], compares rate of heat release curves developed by the aforementioned classes of *t*-squared fires and two test fires commonly used for test purposes. The test fires are shown as dashed lines labeled furniture and 6-ft storage. The dashed curves farther from the origin show the actual rates of heat release of the test fires used in the development of the residential sprinkler and a standard 6-ft high array of test cartons containing foam plastic pails also frequently used as a standard test fire.

The other set of dashed lines in Figure C.2(b) shows these same fire curves relocated to the origin of the graph. This is a more appropriate comparison with the generic curves. As can be seen, the rate of growth in these fires is actually faster than that prescribed for an ultra-fast fire. Such is appropriate for a test fire designed to challenge the fire suppression system being tested.

Figure C.2(c) relates the classes of *t*-squared fire growth curves to a selection of actual fuel arrays extracted from NFPA 204, *Guide for Smoke and Heat Venting*. The individual arrays are also described in Appendix B.

**FIGURE C.2(b) *t*-squared fire, rates of energy release.**

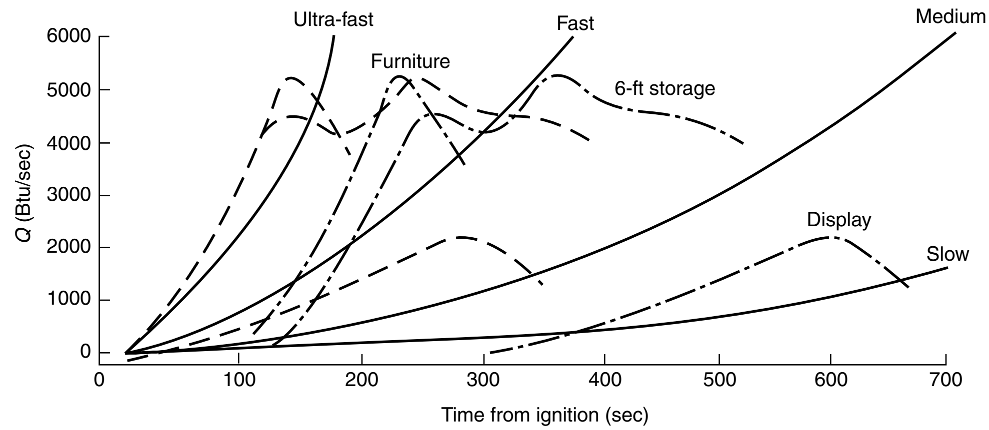
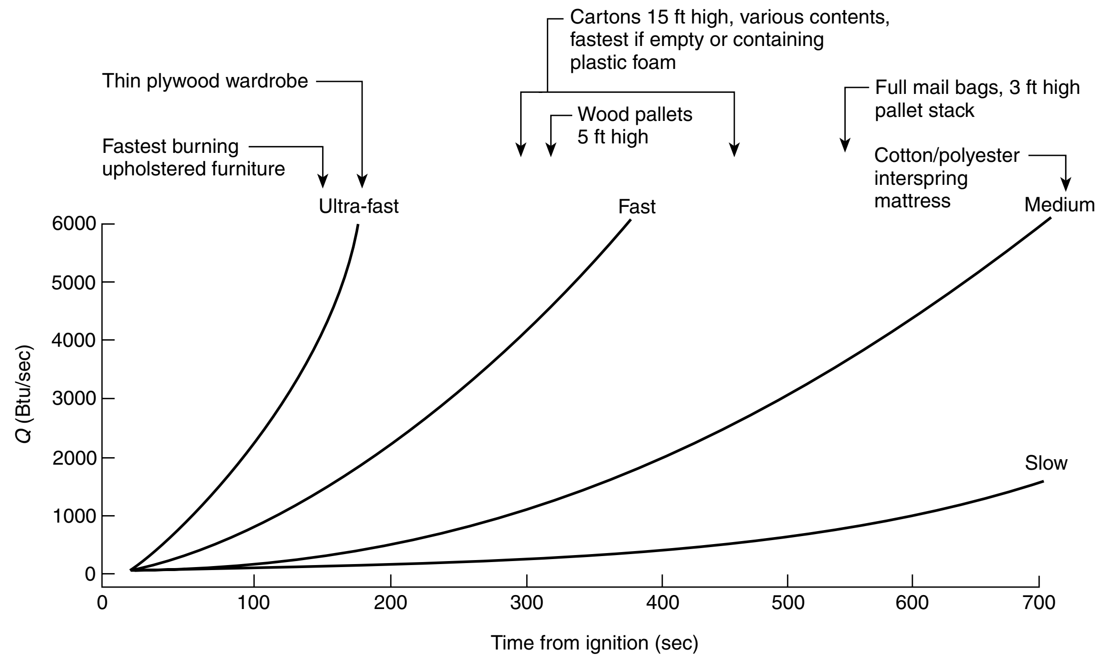



**FIGURE C.2(c) Relation of *t*-squared fires to some fire tests.**




## Appendix D Chapter 3 Equations Using SI Units

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

**Equation (1)**

$$R = \left(\frac{Q}{12\pi q''}\right)^{1/2}$$

**Equation (2)**

$$Q = 1000\left(\frac{t}{t_g}\right)^2$$

where:

$Q$ = heat release rate from fire (kW)
$t$ = time after effective ignition (sec)
$t_g$ = growth time (sec)

**Equation (3)**

$$\frac{z}{H} = 1.11 - 0.28 \ln\left(\frac{tQ^{1/3} / H^{4/3}}{A/H^2}\right)$$

where:

$z$ = height of the first indications of smoke above the fire surface (m)
$H$ = ceiling height above the fire surface (m)
$t$ = time (sec)
$Q$ = heat release rate from steady fire (kW)
$A$ = cross-sectional area of the space being filled with smoke ($m^2$)

**Equation (4)**

$$\frac{z}{H} = 0.91\left(\frac{t}{t_g^{2/5} H^{4/5} (A/H^2)^{3/5}}\right)^{-1.45}$$

see Equation (3) for nomenclature, and
$t_g$ = growth time (sec)

**Equation (5)**

$$m = \frac{Q\Delta t}{H_c}$$

where:
$m$ = total fuel mass consumed (kg)
$Q$ = heat release rate of fire (kW)
$\Delta t$ = duration of fire (sec)
$H_c$ = heat of combustion of fuel (kJ/kg)

**Equation (6)**

$$m = \frac{333\Delta t^3}{H_c t_g^2}$$

see Equation (4) for nomenclature, and
$t_g$ = growth time (sec)

**Equation (7)**

$$z_l = 0.166 Q_c^{2/5}$$

where:
$z_l$ = limiting flame height (m)
$Q_c$ = convective portion of heat release rate (kW)

**Equation (8)**

$$m = 0.071 Q_c^{1/3} z^{5/3} + 0.0018 Q_c \qquad (z > z_l)$$

**Equation (9)**

$$m = 0.032 Q_c^{3/5} z \qquad (z \le z_l)$$

see Equation (8) for nomenclature

**Equation (10)**

$$m = 0.36(QW^2)^{1/3} (Z_b + 0.25H)$$

where:
$m$ = mass flow rate in plume (kg/sec)
$Q$ = heat release rate (kW)
$W$ = width of the plume as it spills under the balcony (m)
$Z_b$ = height above the balcony (m)
$H$ = height of balcony above fuel (m)

**Equation (12)**

$$Q = 1260 A_w H_w^{1/2}$$

where:
$Q$ = heat release rate (kW)
$A_w$ = area of ventilation opening ($m^2$)
$H_w$ = height of ventilation opening (m)

**Equation (13)**

$$a = 2.40 A_w^{2/5} H_w^{1/5} - 2.1 H_w$$

where:
$a$ = effective height (m)
$A_w$ = area of ventilation opening ($m^2$)
$H_w$ = height of ventilation opening (m)

**Equation (14)**

$$m = 0.071 Q_c^{1/3} (z_w + a)^{5/3} + 0.0018 Q_c$$

where:
$m$ = mass flow rate in plume at height $z_w$ (kg/sec)
$Q_c$ = convective portion of heat release rate (kW)
$z_w$ = height above the top of the window (m)

**Equation (15)**

$$m = 0.68(A_w H_w^{1/2})^{1/3} (z_w + a)^{5/3} + 1.59\ A_w H_w^{1/2}$$

where:
$m$ = mass flow rate in plume at height $z_w$ (kg/sec)
$A_w$ = area of ventilation opening ($m^2$)
$H_w$ = height of ventilation opening (m)
$z_w$ = height above the top of the window (m)
$a$ = effective height (m)

**Equation (16)**

$$d = K_d z$$

where:
$d$ = plume diameter (m)
$z$ = height (m)
$K_d$ = diameter constant *(see 3.8.4)*

**Equation (22)**

$$V = \frac{m}{\rho}$$

where:
$V$ = volumetric rate of smoke production ($m^3$/sec)
$\rho$ = density of smoke (1.2 kg/$m^3$ at 20°C)

**Equation (23)**

$$v = 0.64\ [gH\ (T_f - T_o)/T_f]^{1/2}$$

where:
$v$ = air velocity (m/sec)
$g$ = acceleration of gravity (9.8 m/$sec^2$)
$H$ = height of the opening (m)
$T_f$ = temperature of heated smoke (°K)
$T_o$ = temperature of ambient air (°K)

**Equation (24)**

$$v_e = 0.057\ [Q/z]^{1/3}$$

where:

$v_e$ = air velocity (m/sec)

$Q$ = heat release rate (kW)

$z$ = distance above the base of the fire to the bottom of the opening (m)

## Appendix E Example Problems Illustrating the Use of the Equations in NFPA 92B

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

**E.1 Problem Data.** *Given:* Atrium with uniform rectangular cross-sectional area.

| | |
|---|---|
| Height | 120 ft |
| Area | 20,000 ft$^2$ |
| $A/H^2$ | 1.4 |
| Design fire (steady state) | 5000 Btu/sec |
| Highest walking surface | 94 ft |

**E.1.1** *Problem 1.* Determine the time when the first indication of smoke is 6 ft above the highest walking surface.

*Solution:*

(a) Use Equation (3):

$$\frac{z}{H} = 0.67 - 0.28\ \ln\left(\frac{tQ^{1/3}\ /H^{4/3}}{A/H^2}\right)$$

| | |
|---|---|
| $z$ | 100 ft |
| $H$ | 120 ft |
| $Q$ | 5000 Btu/sec |
| $Q^{1/3}$ | 17.1 |
| $H^{4/3}$ | 591.9 |
| $A/H^2$ | 1.4 |

$$0.83 = 0.67 - 0.28\ \ln\left(\frac{17.1\,t/591.9}{1.4}\right)$$

$$0.16 = -0.28\ \ln\left(\frac{0.03\,t}{1.39}\right)$$

$0.16 = -0.28\ \ln\ [0.02t]$

$-0.57 = \ln[0.02t]$

$0.56 = 0.02t$

$t$ = 28 seconds

(b) Use the mass flow method, based on Equation (8).

Two calculation methods will be used. The first calculation will assume a smoke density of 0.075 lb/ft$^3$. This is equivalent to smoke at a temperature of 70°F. The second calculation assumes the layer temperature is equal to the average plume temperature at the height of the smoke layer interface. In both cases, no heat loss from the smoke layer to the atrium boundaries is assumed. A time interval of 1 second is chosen for each case.

(1) Calculation 1 — No smoke density correction.

*Step 1.* Calculate mass flow (lb/sec) at $z = H$, using Equation (8).

*Step 2.* Convert mass flow to volume flow, assuming smoke temperature is 70° F, as follows:

$$V = 60\frac{m}{\rho}$$

where:

$V$ = volume flow (ft$^3$/min)

$m$ = mass flow (lb/sec)

$\rho$ = density of smoke (lb/ft$^3$)

*Step 3.* Assume that the smoke volume produced in the selected time interval is instantly and uniformly distributed over the atrium area. Determine the depth of the smoke layer, $dz$ (ft), deposited during the selected time period.

*Step 4.* Calculate the new smoke layer interface height (ft).

Repeat steps (1)–(4) until the smoke layer interface reaches the design height.

Table E.1, showing sample values, illustrates the calculation technique.

**E.1.2** *Problem 2.* Determine the volumetric exhaust rate required to keep smoke 5 ft above the highest walking level in the atrium, that is, the ninth floor balcony. Consider the fire to be located in the center of the floor of the atrium.

With the fire located in the center of the atrium, an axisymmetric plume is expected. First, Equation (7) must be applied to determine the flame height.

*Given:*

$Q_c$ = 3500 Btu/sec

$z_l = 0.533\ Q_c^{2/5}$

$z_l = 0.533\ (3500)^{2/5}$

$z_l$ = 13.9 ft

With the design interface of the smoke layer at 85 ft above floor level, the flame height is less than the design smoke layer height. Thus, using Equation (8) to determine the smoke production rate at the height of the smoke layer interface:

$z$ = 85 ft

$m = 0.022\ Q_c^{1/3}\ z^{5/3} + 0.0042\ Q_c$

$m = 0.022\ (3500)^{1/3}\ (85)^{5/3} + 0.0042\ (3500)$

$m$ = 564 lb/sec

If the smoke exhaust rate is equal to the smoke production rate, the smoke layer depth will be stabilized at the design height. Thus, converting the mass flow rate to a volumetric flow rate as follows:

$$V = \frac{m}{\rho}$$

where:

$\rho$ = 0.075 lb/ft$^3$

$V$ = 564/0.075

$V$ = 7521 ft$^3$/sec, or 451,260 scfm

**Table E.1 Sample Calculated Values**

| Time (sec) | $z$ (ft) | Mass (lb/sec) | Vol ($ft^3$/sec) |
|---|---|---|---|
| 1 | 119.3 | 990 | 13,199 |
| 2 | 118.7 | 981 | 13,080 |
| 3 | 118.0 | 972 | 12,963 |
| 4 | 117.4 | 964 | 12,847 |
| 5 | 116.8 | 955 | 12,732 |
| 6 | 116.1 | 946 | 12,619 |
| 7 | 115.5 | 938 | 12,508 |
| 8 | 114.9 | 930 | 12,397 |
| 9 | 114.3 | 922 | 12,288 |
| 10 | 113.7 | 914 | 12,181 |
| 11 | 113.1 | 906 | 12,074 |
| 12 | 112.5 | 898 | 11,969 |
| 13 | 111.9 | 890 | 11,866 |
| 14 | 111.3 | 882 | 11,763 |
| 15 | 110.7 | 875 | 11,662 |
| 16 | 110.1 | 867 | 11,562 |
| 17 | 109.5 | 860 | 11,463 |
| 18 | 109.0 | 852 | 11,366 |
| 19 | 108.4 | 845 | 11,270 |
| 20 | 107.9 | 838 | 11,174 |
| 21 | 107.3 | 831 | 11,080 |
| 22 | 106.7 | 824 | 10,987 |
| 23 | 106.2 | 817 | 10,895 |
| 24 | 105.7 | 810 | 10,804 |
| 25 | 105.1 | 804 | 10,715 |
| 26 | 104.6 | 797 | 10,626 |
| 27 | 104.1 | 790 | 10,538 |
| 28 | 103.5 | 784 | 10,451 |
| 29 | 103.0 | 777 | 10,366 |
| 30 | 102.5 | 771 | 10,281 |
| 31 | 102.0 | 765 | 10,197 |
| 32 | 101.5 | 759 | 10,115 |
| 33 | 101.0 | 752 | 10,033 |
| 34 | 100.5 | 746 | 9,952 |
| 35 | 100.0 | 740 | 9,872 |

**E.1.3** *Problem 3.* Determine whether the plume will contact all of the walls prior to reaching the design height noted in Problem 2 (5 ft above the highest walking level).

The calculation in Problem 2 assumes that the smoke plume has not widened to contact the walls of the atrium prior to reaching the design interface height. This calculation serves as a check.

Using Equation (16) with an interface height of 85 ft ($z$ = 85 ft),

$d = 0.5z$
$d = 0.5(85)$
$d = 42.5$ ft

Thus, the smoke does not contact the walls of the atrium prior to reaching the design interface height.

**E.1.4** *Problem 4.* Determine the temperature of the smoke layer after fan actuation.

The quality of the smoke contained in the smoke layer might be important in the context of tenability or damageability studies. Applying Table 3.5:

*Given:*
$Q_c = 3500$ Btu/sec
$\rho = 0.075$ lb/$ft^3$
$c = 0.24$ Btu/lb-°F
$V = 7521$ $ft^3$/sec
$\Delta T = Q_c/(\rho c V)$
$\Delta T = 3500/[(0.075)(0.24)(7521)]$
$\Delta T = 26$°F

**E.1.5** *Problem 5.* On the tenth floor, a 10 ft wide × 6 ft high opening is desired from the tenant space into the atrium.

(a) For a fire in the tenant space, determine the opposed airflow required to contain smoke in the tenant space (assume fire temperature is 1000°F).

Using Equation (23), 3.13.1:

*Given:*
$H = 6$ ft
$g = 32.2$ ft/$sec^2$
$T_f = 1000$°F
$T_o = 70$°F
$v = 38.4[gH(T_f - T_o)/(T_f + 460)]^{1/2}$
$v = 38.4[(32.2)(6)(1000 - 70)/(1000 + 460)]^{1/2}$
$v = 426$ ft/min

(b) For a fire in the atrium, determine the opposed airflow required to restrict smoke spread into the tenant space.

*Given:*
$Q = 5000$ Btu/sec
$z = 90$ ft

$v_e = 17\,[Q/z]^{1/3}$
$v_e = 17\,[5000/90]^{1/3}$
$v_e = 64.8$ ft/min

## Appendix F Referenced Publications

**F.1** The following documents or portions thereof are referenced within this guide for informational purposes only and are thus not considered part of its recommendations. The edition indicated here for each reference is the current edition as of the date of the NFPA issuance of this guide.

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

NFPA 13, *Standard for the Installation of Sprinkler Systems*, 1999 edition.

NFPA 72, *National Fire Alarm Code*®, 1999 edition.

NFPA 204, *Guide for Smoke and Heat Venting*, 1998 edition.

NFPA 909, *Standard for the Protection of Cultural Resources, Including Museums, Libraries, Places of Worship, and Historic Properties*, 1997 edition.

**F.1.2 Other Publications.**

**F.1.2.1 ASHRAE Publication.** American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc., 1791 Tullie Circle, N.E., Atlanta, GA 30329-2305.

ASHRAE *Handbook of Fundamentals*, 1997.

**F.1.2.2 ASTM Publications.** American Society for Testing and Materials, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959.

ASTM E 1321, *Standard Test Method for Determining Material Ignition and Flame Spread Properties*, 1997.

ASTM E 1354, *Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*, 1997.

**F.1.3 Additional References.**

1. Morgan, H. P., *Smoke Control Methods in Enclosed Shopping Complexes of One or More Storeys: A Design Summary*, Building Research Establishment, 1979.

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