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# NFPA 92B
# Smoke Management Systems in Malls, Atria, and Large Areas
## 1991 Edition

NFPA®

National Fire Protection Association, 1 Batterymarch Park, PO Box 9101, Quincy, MA 02269-9101

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**NFPA 92B**

**Guide for**

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

**1991 Edition**

This first 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, released by the Correlating Committee on Building Construction, and acted on by the National Fire Protection Association, Inc. at its Fall Meeting held November 12-14, 1990 in Miami, FL. It was issued by the Standards Council on January 11, 1991, with an effective date of February 8, 1991.

The 1991 edition of this document has been approved by the American National Standards Institute.

## Origin and Development of NFPA 92B

The NFPA Standards Council established the Technical Committee on Smoke Management Systems in 1985 and charged it with addressing the need for guidelines and materials on building fire smoke management. The Committee's first document, NFPA 92A, *Recommended Practice for Smoke Control Systems*, was published in 1988 and addresses smoke control utilizing barriers, airflows, and pressure differentials so as to confine the smoke of a fire to the zone of fire origin and thus maintain a tenable environment in other zones. The complex problem of maintaining tenable conditions within large zones of fire origin, such as atria and shopping malls, represents a more difficult issue in terms of the physics involved and thus was reserved for this new document, NFPA 92B, *Guide for Smoke Management Systems in Malls, Atria, and Large Areas*.

The Technical Committee on Smoke Management Systems acknowledges the extraordinary, dedicated efforts of the following individuals, without whose collective expertise and cooperation this document would not have been completed in the timely fashion that it was and would not have covered the technical subject as exhaustively as it does: John Campbell, Gunnar Heskestad, John Kampmeyer, James Milke, Harold Nelson, William Schmidt, Reed Varley, Alvin Vener, and William Webb.

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# NFPA 92B

## Guide for

# Smoke Management Systems

# in Malls, Atria, and Large Areas

## 1991 Edition

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

Information on referenced publications can be found in Chapter 6 and Appendix G.

## 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, non-compartmented spaces. This publication documents:

(a) The problem

(b) Basic physics of smoke movement in indoor spaces

(c) Methods of smoke management

(d) Data and technology

(e) Building equipment and controls

(f) Test and maintenance methods.

**1-2* Scope.** This guide provides technical data relevant to the design, installation, testing, operation, and maintenance of new and retrofitted smoke management systems 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. Such buildings 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 204M, *Guide for Smoke and Heat Venting*, for gravity venting. This guide is not intended to apply to warehouses, manufacturing facilities, or other similar spaces.

**1-3 Purpose.**

**1-3.1** The purpose of this guide is to provide guidance in implementing smoke management systems to accomplish one or more of the following:

(a) Maintain a tenable environment in the means of egress from large volume building spaces during the time required for evacuation.

(b) Control and reduce the migration of smoke between the fire area and adjacent spaces.

(c) Provide conditions within and outside the fire zone that will assist emergency response personnel to conduct search and rescue operations and to locate and control the fire.

(d) Contribute to the protection of life and reduction of property loss.

(e) Aid in post-fire smoke removal.

**1-3.2** Specific design objectives may 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 shall have the meanings given in this chapter.

**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 communication facilities.

**Communicating Space.** Spaces within a building that have an open pathway to a large volume space such that smoke from a fire in the communicating space can move unimpeded into the large volume space. Communicating spaces may open directly into the large volume space or may connect through open passageways.

**Covered Mall.** A large volume space created by a roofed-over common pedestrian area in a building enclosing a number of tenants and occupancies such as retail stores, drinking establishments, entertainment and amusement facilities, offices, or other similar uses where tenant spaces open onto or directly communicate with the pedestrian area.

**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. Atria and covered malls are examples of large volume spaces.

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

**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.

**Smoke Barrier.** A 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 may or may not have a fire resistance rating. Smoke barriers may have openings that are protected by automatically closing devices or by airflows adequate to control movement of smoke through the opening.

**Smoke Damper.** A device that meets the requirements of UL 555S, *Standard for 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 Fire Dampers*, and UL 555S, *Standard for Leakage Rated Dampers for Use in Smoke Control Systems*.

**Smoke Layer.** The accumulated thickness of smoke below a physical or thermal barrier.

**Smoke Layer Interface.** The boundary between a smoke layer and smoke-free air.

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

**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.

**Supervision.** A self-testing feature of a smoke management system whereby circuit conductors or device functions are monitored for integrity, and failure of the conductors or device produces visual and audible trouble indications.

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

**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. Then the space can be expected to begin to fill with smoke, with the smoke layer interface descending. The descent rate of the smoke layer interface depends on the rate at which smoke is supplied to the smoke layer from the plume. This assumes a two-zone model in which there is a distinct interface between the bottom of the smoke layer and the ambient air. For engineering purposes, the smoke supply rate from the plume can be estimated to be the air entrainment rate into the plume below the smoke layer interface. Sprinklers may reduce the heat release rate and the air entrainment rate into the plume.

**1-5.1.2** 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.

**1-5.1.3** 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 may be substantial.

**1-5.1.4** In order for the 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 air must 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 may show that no additional venting is required. Alternatively, whether communicating spaces are sprinklered or not, smoke may 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** The amount of smoke produced by a fire is a function of the heat release of the fire and the height of the smoke layer above the fire.

**1-5.4.2** Automatic suppression systems are designed to limit fire size and will, therefore, limit smoke generation. Fires in spaces adjacent to atria and covered mall pedestrian areas can also be effectively limited so as to cause minimal effect upon atrium spaces or covered mall pedestrian areas.

**1-5.4.3** Activation of sprinklers near a fire will cause cooling of the smoke, resulting in a loss of buoyancy. This may cause smoke to descend and visibility to be reduced.

**1-5.5** The smoke management system components should be rated for continuous use at the maximum temperatures expected, using the calculations contained in this guide.

**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:

(a) 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*).

(b) Large openings in smoke barriers, such as open doors and other sizable openings, may 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 its direction and magnitude. The stack effect must be considered in selection of exhaust fans. The effect of temperature and wind velocity will vary 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** The design objectives contained in Chapter 1 can be met by a variety of methodologies. Some of those are further explained in Chapter 2.

## Chapter 2 Design Considerations

### 2-1 Design Options.

**2-1.1 Methodologies.** Design objectives will 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 may be a fire within the large volume space or within the communicating space. Examples of objectives include:

(a) Maintain the smoke layer interface to a predetermined elevation.

(b) Maintain a tenable environment on all exit access and area of refuge access paths for a sufficient time to allow all occupants to reach an exit or area of refuge.

(c) Limit the spread of smoke from the fire/smoke zone into other zones that may be exits, exit access routes, areas of refuge, or communicating spaces.

(d) Provide adequate visibility to allow fire department personnel to approach, locate, and extinguish the fire.

(e) Exhaust smoke that has accumulated in the large volume space within a specified time.

(f) Limit the smoke layer temperature.

**2-1.2 Method Selection.** The design options available depend on the space in which the smoke is to be managed and the source of the smoke as described in the following:

**2-1.2.1 Management of Smoke in Large Volume Space.**

(a) Fire in large volume space is source of smoke.

1. Remove smoke from the large volume space to limit the depth of smoke accumulation within that space, or

2. Remove smoke from the large volume space at a rate sufficient to increase the time for smoke filling of that space.

(b) Fire originates in communicating space.

1. Remove any smoke that enters the large open space to limit the depth of smoke accumulation or delay the smoke filling within the large open space, or

2. Prevent smoke from entering the large open space by opposed airflow.

**2-1.2.2 Management of Smoke in Communicating Space.**

(a) Fire originates in large volume space.

1. Remove smoke from 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 depth remains above the level of communication between spaces for the time necessary to achieve the design objectives. This technique may not be completely effective if the source of the fire is directly adjacent to the communicating space. This approach is not feasible for communicating spaces in the upper portion of the large volume space, or/and

2. Exhaust the large volume space so that it is at a negative pressure with respect to the communicating space. This is discussed, with some limitations for use in a large volume space, in NFPA 92A, *Recommended Practice for Smoke Control Systems*, or/and

3. Use airflow as discussed in this document and/or barriers as discussed in NFPA 92A.

(b) Fire originates within the communicating space. The management of smoke within this space is discussed in NFPA 92A. In general, it will not be possible to manage smoke within such a space without the use of physical barriers to limit smoke movement or methods to limit smoke production such as controlling the fuel or using automatic fire suppression.

**2-1.3 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 must be given to:

(a) Type and location of occupancies within and communicating with the large volume space. The height, size, and arrangement of openings between the occupancy within the communicating space and the large volume space are important considerations.

(b) Barriers, if any, that separate the communicating space with the large volume space.

(c) Egress routes from the large volume space and any communicating space.

(d) Areas of refuge, either temporary or indefinite.

(e) Design basis fire used to calculate the smoke production. This may be limited by fuel, automatic suppression, or ventilation.

**2-2 Design Limitations.**

**2-2.1 Smoke Accumulation Depth.** It is not a realistically achievable design objective to prevent accumulation of smoke within the upper portions of a large volume space under most realistic fire scenarios.

**2-2.2 Disruption of Smoke Depth Interface.** Operation of automatic fire suppression systems can drive the level of smoke accumulation below the design depth.

**2-3 Design Features.**

**2-3.1 Fault Analysis.** Every smoke management system should be subjected to a fault analysis to determine the impact on intended system operation of a failure, improper operation, or partial operation of each major system component. Of particular concern will be those systems that are intended to maintain a pressure or flow balance between adjacent spaces to control the movement of smoke. Should it be found that the faulty operation of a component will cause reversal of the smoke flow or lowering of the smoke interface layer to dangerous levels, the degree to which its operation may be reduced and the probability of such occurrence should be determined.

**2-3.2 Reliability.** Reliability of the smoke management system depends on the specific reliability of the individual components, functional dependence of the components on one another, and degree of redundancy. Reliability of the individual components (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 examined by an independent testing laboratory. However, listing/classification of the component is not self-sufficient to ensure reliability of the components. 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. Also, frequent maintenance and testing are needed to assess the system reliability throughout the life of the system. Supervision of the system components will enhance the reliability of the system by providing a timely visual or audible indication of component failure and will facilitate prompt repair.

**2-3.3 Periodic Testing.** Periodic testing is essential to ensure the system is operational and will reliably perform when needed. Means should be provided for performing periodic tests of the smoke management system in order 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 built-in or partially built-in and partially provided as portable monitors.

**2-4 Fire in the Large Volume Space.**

**2-4.1** Smoke management systems for large volume spaces are intended to control 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 are needed to accomplish these goals:

(a) The fire must be detected early, that is before the smoke level or rate of descent exceeds the design objectives. When the smoke management system is provided to assist safe evacuation, occupant reaction time to the emergency and evacuation time should be considered.

(b) The HVAC system serving the large volume space and communicating spaces must be stopped if its operation would adversely affect the smoke management system.

(c) Smoke should be removed in the large volume space above the desired smoke layer interface.

(d) 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.

**2-4.2 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 must be evaluated. These factors vary widely among atrium designs and must be considered carefully in selecting detectors for a large volume space. In addition, the envelope of the large volume space must be evaluated for its contribution to temperature stratification. The height of the large volume space and its architectural features such as skylights will be dominant factors in determining stratification.

**2-4.2.1** Environmental factors such as convection currents and mechanical air movement also must be considered in selecting detector type and location. NFPA 72E, *Standard on Automatic Fire Detectors*, provides guidance. The automatic activation of the smoke management system can be initiated by:

(a) Spot-type smoke detectors

(b) Beam-type smoke detectors

(c) Automatic sprinkler system waterflow

(d) Other detectors found to be suitable

(e) Combinations of the above.

**2-4.2.2** 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 may be an exception. In order 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 upon 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 the following:

NFPA 71, *Standard for the Installation, Maintenance, and Use of Signaling Systems for Central Station Service*.

NFPA 72, *Standard for the Installation, Maintenance, and Use of Protective Signaling Systems*.

**2-4.2.3** Spot-type smoke detectors could 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.

**2-4.2.4** Projected beam-type smoke detectors could 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 may necessitate the use of additional projected beams at interim levels of the large volume space where ceiling heights would contribute to the delay in initiating smoke management.

**2-4.2.5** Automatic sprinkler waterflow should also usually 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. Under conditions of multi-story ceiling heights and ceiling-mounted sprinklers, sprinkler activation time may be too slow to effectively initiate smoke management. 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. Under conditions of lower ceiling heights, sprinkler activation may provide an effective primary initiation means.

**2-4.3 Manual Activation.** A means of manually starting and stopping the smoke management system should be at a location accessible to the fire department.

**2-4.4 Exhaust Rate.** The exhaust rate should be established based on the design fire using the procedures contained in Chapter 3 of this guide. Among the factors to be considered are:

(a) The exhaust quantity is determined by the design clear height (allowable depth) of the smoke layer.

(b) In a large volume space with a large height-to-width ratio, the smoke plume can be expected to intersect all sides of the space. The impact of the smoke with the wall must be considered in the design.

**2-4.5 Protecting Communicating Spaces.** Preventing smoke movement from the large volume space into communicating spaces by airflow alone requires a face velocity across the entire opening that exceeds the expected entrainment velocity of a fire plume positioned next to the adjacent space. See Section 3-10 for a calculation method for the minimum face velocity.

**2-4.6** For adjacent spaces below the smoke layer interface, any smoke contamination of those spaces by intersecting plumes can be expected to be limited in lateral extent. Local contamination can be mitigated using the method described in 2-4.5.

**2-5 Fire in Spaces Surrounding Large Volume Space.**

**2-5.1** Possible configurations for the relationship between the large volume space and the surrounding spaces include the following:

(a) Separated space

(b) Communicating space.

**2-5.2 Fire in Separated Spaces.** Where construction separating the large volume space from the surrounding areas is sufficiently tight 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*.

**2-5.3 Fires in Communicating Spaces.**

**2-5.3.1** Communicating spaces may be designed to allow the smoke to spill into the large volume space.

**2-5.3.1.1** In this instance, the smoke spilling into the large volume space should be handled by the smoke management system there to maintain the design smoke layer interface height.

**2-5.3.1.2** The exhaust rate from the large volume space must be evaluated for both the spill plume condition and the free plume from a fire in the large volume space. The smoke management system should be able to handle either condition but not both simultaneously.

**2-5.3.1.3** Once in the large volume space, the possibility of 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 may or may not present to these spaces should be evaluated.

**2-5.3.2** Communicating spaces may also be designed to prevent the movement of smoke into the large volume space.

**2-5.3.2.1** Such a design would require sufficient exhaust from the communicating space to establish a minimum flow between it and the large volume space. Paragraph 2-4.5 describes the face velocity across the face area of the opening to achieve this, and Chapter 3 provides calculation methods for smoke generation in the communicating space.

**2-5.3.2.2** The exhaust quantity necessary for this situation may greatly exceed the capacity of the normal building HVAC systems and may require the installation of a dedicated smoke management system for the communicating space.

**2-5.3.2.3** The placement of the exhaust openings should be carefully evaluated. Exhaust intake and discharge openings should be so located 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.

## Chapter 3 Calculation Procedures

*(See Appendix G for references cited in this chapter.)*

**3-1 Introduction.**

**3-1.1** This section presents the calculation procedures for the various design parameters, as referred to in the previous sections. The calculation procedures represent the best information available for this edition of the guide.

**3-1.2 Scale Modeling.** The calculation procedures in this chapter are based on free rising plumes without significant obstructions in the large volume space. Systems with such obstructions or with unusually complex geometries are a cause of concern. Scale model tests are recommended for such systems. The scaling relations are:

$$v_M / v_B = (H_M / H_B)^{1/2}$$
$$Q_M / Q_B = (H_M / H_B)^{5/2}$$
$$V_M / V_B = (H_M / H_B)^{5/2}$$

where

$v$ = velocity
$Q$ = heat release rate
$V$ = volumetric flow rate
$H$ = height

The subscripts M and B refer to model and building. Models should be at least $1/8$ scale.

**3-1.3 Establishment of Two-Layer Environment.** A delay in activating exhaust fans may allow smoke to descend below the design height of the smoke interface. Initial smoke accumulation at low levels may also be aggravated by initial vertical temperature stratifications that will delay transport of smoke to the upper reaches of the atrium. However, with the exhaust and air makeup systems activated, a clear lower layer can be expected to develop in agreement with the design assumptions.

**3-1.4 SI Units.** SI forms of the equations contained in this chapter are presented in Appendix D.

**3-2 Design Fire.**

**3-2.1*** All of the design calculations are dependent on the heat release rate from the fire. Thus, as a first step, the design fire size must be identified. The design fire size is determined based on an engineering analysis of the characteristics of the fuel and/or effects induced by a fire. 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. 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 may be assumed essentially to 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, i.e., the maximum probable size fuel package that is likely to be involved in fire. The design fire should be increased if other combustibles are within the separation distance, R, indicated in Figure 3-1 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, e.g., if the fuel package consists of the furniture items illustrated in Figure 3-2, the area of the fuel package includes that covered by the furniture as well as the area between the furniture items.

$$R = [Q/(12\pi q'')]^{1/2} \qquad (1)$$

where

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

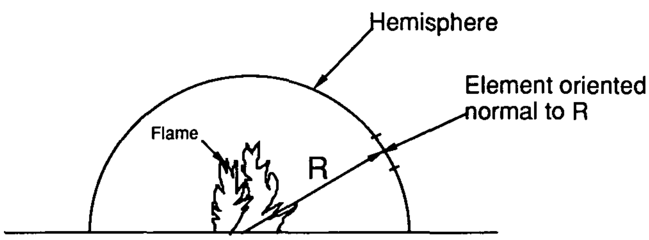


**Figure 3-1 Separation distance, R.**

**3-2.2.3** Specification of a fixed design fire size applicable to all situations is not realistic. The design fire size needs to be sensitive to variations in the type and amount of fuel.

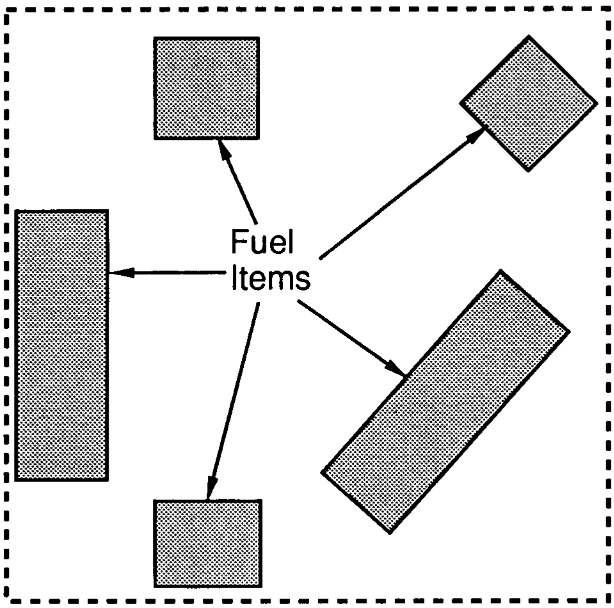


Figure 3-2 Fuel items.

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):

$$Q = 1000\ (t/t_g)^2 \qquad (2)$$

where

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

$t_g$ is the time interval from the time of effective ignition until the fire exceeds 1000 Btu/s. See Appendix C for further information on t-squared profile fires.

A t-square profile can be used for engineering purposes until large areas become involved, due to the dynamics of secondary ignitions. Thus, a t-square profile is reasonable up 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 has been reported [2,3]. (*See Appendix B.*) However, furniture construction details and materials are known to influence substantially the peak heat release rate, such that heat release rate data is not available for all furniture items nor for "generic" furniture items.

**Table 3-2 Excess Gas Temperature at the Time of Automatic Sprinkler Actuation (Steady Fires)**

| $Q_c$ (Btu/s) | RTI $(ft\text{-}s)^{1/2}$ | Gas Temperature Minus Temperature Rating (°F) H=13 ft | H=26 ft | H=52 ft | H=79 ft | H=105 ft | H=131 ft |
|---|---|---|---|---|---|---|---|
| 16000 | 54 | 725 | 234 | 47 | 32 | 29 | – |
| | 180 | >1000 | 322 | 74 | 36 | 31 | – |
| | 630 | >1000 | 484 | 128 | 49 | 32 | – |
| 8000 | 54 | 527 | 137 | 40 | 32 | – | – |
| | 180 | 731 | 202 | 49 | 32 | – | – |
| | 630 | >1000 | 313 | 72 | 34 | – | – |
| 4000 | 54 | 360 | 74 | 38 | – | – | – |
| | 180 | 475 | 122 | 38 | – | – | – |
| | 630 | 563 | 202 | 43 | – | – | – |
| 2000 | 54 | 207 | 50 | – | – | – | – |
| | 180 | 311 | 74 | – | – | – | – |
| | 630 | 472 | 117 | – | – | – | – |
| 1000 | 54 | 113 | 43 | – | – | – | – |
| | 180 | 184 | 49 | – | – | – | – |
| | 630 | 306 | 70 | – | – | – | – |

$Q_c$ = convective portion of heat release rate
RTI = response time index
H = ceiling height above fire source
"–" means that the automatic sprinkler does not operate in a time interval for which temperature data are available

**3-2.4.2** If heat release rate data is unavailable for specific fuel items, an average heat release rate for the design fuel area can be estimated. A typical heat release rate per unit floor area in office buildings is 20 Btu/ft$^2$-sec [4,5] and 44 Btu/ft$^2$-sec for mercantile occupancies [1] and residential rooms, respectively [6].

**3-2.5 Caution.** Designers or analysts are strongly cautioned from suggesting that few combustibles will be included in the space, thereby limiting the rate of heat release below 1000 Btu/sec. Such a condition may not be possible to maintain during the life of the building for all times of day, days of the week, or seasons of the year.

**3-3 Fire Detection and Sprinkler Actuation.**

**3-3.1 General.** 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 radius from the fire axis. However, for radius to ceiling height ratios of 0.6 or less, the temperature rise at any radius is approximately equal to that directly over the fire.

**3-3.2 Response Temperature.**

**3-3.2.1 Ceiling Mounted Spot Smoke Detectors.** The response of a ceiling mounted spot smoke detector can be estimated in a manner similar to that for a sprinkler by considering a given temperature rise of the fire gases [7], depending on the particular detector model and fire source. A realistic temperature rise indicative of a concentration of smoke from common fuels that would cause detection by a reasonably sensitive spot detector is approximately 20°F (approximately 10°C).

**3-3.2.2 Ceiling Mounted Fixed Temperature Detectors.** With no thermal lag and no conductive heat loss to the sprinkler piping, the temperature rise at actuation for a 165°F (74°C) rated automatic sprinkler would typically be 97°F (36°C). However, the conditions of "no thermal lag" and "no conductive heat loss" are not realistic. Allowing for thermal lag and conductive heat loss, the response of the fixed temperature detector is a function of the temperature rating, response time index (RTI), a conduction parameter, and the gas temperature and gas velocity [8]. A representative value of the conduction parameter for commercial sprinklers is 1.8 ft$^{1/2}$/sec$^{1/2}$ (1 m$^{1/2}$/s$^{1/2}$).

**3-3.2.2.1 Steady Fires.** The approximate gas temperature at actuation of automatic sprinklers can be determined from the information provided in Table 3-2. The temperatures noted in the table are the differences between the gas temperature and the sprinkler temperature rating of approximately 165°F (74°C) at actuation for the noted ranges of RTI, ceiling height, and fire size [9]. For values not indicated in the table, linear interpolation can be used. The associated time for actuation, t, can be estimated by using Equation (3), with the temperature rise being the determined gas temperature (evaluated using Table 3-2) minus the ambient temperature.

**3-3.2.2.2 Unsteady Fires.** The approximate gas temperature at actuation of automatic sprinklers can be determined from the information provided in Table 3-3. The temperatures noted in the table are the difference between the gas temperature and the sprinkler temperature rating of approximately 165°F (74°C) at actuation for the noted ranges of RTI, ceiling height, and fire growth rate, given a t-squared type fire [9]. For values not indicated in the table, linear interpolation can be used. The associated time for actuation, t, can be estimated by using Equation (4), with the temperature rise being the determined gas temperature (evaluated using Table 3-3) minus the ambient temperature.

**3-3.3** The temperature of the smoke under the ceiling can be estimated by the methods presented in 3-3.4 and

**Table 3-3 Excess Gas Temperature at the Time of Automatic Sprinkler Actuation (Unsteady Fires)**

| | | Gas Temperature Minus Temperature Rating (°F) | | | | |
|---|---|---|---|---|---|---|
| $t_g$ (s) | RTI (ft-s)$^{1/2}$ | H=13 ft | H=26 ft | H=52 ft | H=105 ft | H=210 ft |
| 50 | 54 | 122 | 74 | 47 | 36 | 27 |
| | 180 | 236 | 130 | 72 | 45 | 31 |
| | 630 | 472 | 263 | 143 | 76 | 43 |
| 100 | 54 | 90 | 58 | 43 | 34 | 27 |
| | 180 | 162 | 92 | 54 | 38 | 29 |
| | 630 | 324 | 178 | 95 | 54 | 34 |
| 200 | 54 | 72 | 52 | 40 | 32 | 27 |
| | 180 | 113 | 68 | 47 | 34 | 27 |
| | 630 | 223 | 121 | 68 | 43 | 31 |
| 400 | 54 | 63 | 49 | 40 | 32 | 27 |
| | 180 | 85 | 56 | 41 | 32 | 27 |
| | 630 | 151 | 85 | 52 | 38 | 29 |
| 800 | 54 | 58 | 47 | 38 | 32 | 27 |
| | 180 | 68 | 50 | 40 | 32 | 27 |
| | 630 | 106 | 65 | 45 | 34 | 27 |

$T_g$ = growth time
RTI = response time index
H = ceiling height above fire source

3-3.5, as long as the smoke layer does not stratify prematurely (*see Section 3-4*).

**3-3.4 Steady Fires.** For radius-to-ceiling height ratios less than approximately 0.6, the temperature rise of the smoke under the ceiling can be estimated as a function of time based on a theoretical generalization of the limited amount of experimental data [10]. For $X \leq 480$:

$$X = 4.6 \times 10^{-4} Y^2 + 2.7 \times 10^{-15} Y^6 \qquad (3)$$

where

$X = tQ^{1/3}/H^{4/3}$
$Y = \Delta T\ H^{5/3}/Q^{2/3}$

and where

$t$ = time from ignition (s)
$Q$ = heat release rate (steady fire) (Btu/s)
$H$ = ceiling height above the fire surface (ft)
$\Delta T$ = temperature rise under the ceiling (°F)

**3-3.5 Unsteady Fires.** For t-square fires [*see Equation (2)*], the temperature rise of the smoke under the ceiling associated with radius-to-ceiling height ratios less than approximately 0.6 can be estimated as a function of time, based on a theoretical generalization of the limited amount of experimental data [10]:

$$\Delta T = 27{,}400\ [t/(t_g^{2/5}H^{4/5}) - 0.22]^{4/3}/\ [t_g^{4/5}H^{3/5}] \qquad (4)$$

($\Delta T$ in °F; $t$ and $t_g$ in s; $H$ in ft)

**3-4 Stratification of Smoke.**

**3-4.1** The upward movement of smoke in the plume is dependent upon the smoke being buoyant relative to the surroundings. The potential for stratification relates to the difference in temperature at the ceiling and floor levels of the open space [11]. There is a maximum height to which plume fluid (smoke) will rise, especially early after ignition, depending on the convective heat release rate and the ambient temperature variation in the open space. This maximum rise can be derived from the pioneering work of Morton, Taylor, and Turner [11].

$$z_m = 14.7\ Q_c^{1/4}\ (dT/dz)^{-3/8} \qquad (5)$$

where

$z_m$ = maximum height of smoke rise above fire surface (ft)
$Q_c$ = convective portion of the heat release rate (Btu/s)
$dT/dz$ = rate of change of ambient temperature with respect to height (°F/ft)

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

**3-4.2** Assuming that the ambient temperature varies linearly with height, the minimum $Q_c$ required to overcome the ambient temperature difference and drive the smoke to the ceiling ($z_m = H$) follows readily from equation (5).

$$Q_{c,min} = 2.39 \times 10^{-5}\ H^{5/2}\Delta T_0^{3/2} \qquad (6)$$

where

$Q_{c,min}$ = minimum convective heat release rate to overcome stratification (Btu/s)
$H$ = ceiling height above fire surface (ft)
$\Delta T_0$ = 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:

$$\Delta T_0 = 1300\ Q_c^{2/3}H^{-5/3} \qquad (7)$$

Finally, as a third alternative, the maximum ceiling clearance to which a plume of strength $Q_c$ can rise for a given $\Delta T_0$ follows from rewriting Equation (7):

$$H_{max} = 74\ Q_c^{2/5}\Delta T_0^{-3/5} \qquad (8)$$

**3-5 Height of Smoke Layer Interface at Any Time.**

**3-5.1 General.** The position of the smoke layer interface at any time can be determined from the relations in this section. The relations address three situations:

(a) No smoke exhaust is operating (*see 3-5.2*).

(b) The mass rate of smoke exhaust equals the mass rate of smoke supplied from the plume to the smoke layer (*see 3-5.3.1*).

(c) The mass rate of smoke exhaust is less than the rate of smoke supplied from the plume to the smoke layer (*see 3-5.3.2*).

**3-5.2 Position of Smoke Layer Interface with No Smoke Exhaust Operating.**

**3-5.2.1 Steady Fires.** For steady fires, the height of the smoke layer interface above the fire surface, z, can be estimated for any time, t, from Equation (9) (where calculations yielding $z/H > 1.0$ mean that the smoke layer has not yet begun to descend):

$$z/H = 0.67 - 0.28 \ln [(tQ^{1/3}/H^{4/3})/(A/H^2)] \qquad (9)$$

where

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

Equation (9) is based on experimental data from investigations with $A/H^2$ ratios in the range from 0.9 to 14 [7,12,13,14]. This equation is for the worst case condition, a fire away from any walls.

**3-5.2.2 Unsteady Fires.** The descent of the smoke layer interface can also be estimated for certain types of unsteady fires, e.g., t-square fires. From basic theory and limited experimental evidence, the height of the smoke interface 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):

$$z/H = 0.23\ [t/(t_g^{2/5}\ H^{4/5}\ (A/H^2)^{3/5})]^{-1.45} \quad (10)$$

($t$ and $t_g$ in s; H in ft; A in $ft^2$; as previously defined)

This equation is for the worst case condition, a fire away from any walls.

**3-5.2.3** The equations presented in 3-5.2.1 and 3-5.2.2 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:

$$m = Q\ \Delta t\ /\ H_c \quad (11)$$

where

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

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

$$m = 333\Delta t^3\ /\ (H_c t_g^2) \quad (12)$$

($t_g$ in s as previously defined)

**3-5.3 Position of Smoke Layer Interface with Smoke Exhaust Operating.**

**3-5.3.1 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 will be 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 3-6 for the mass rate of smoke supplied to the base of the smoke layer for different plume configurations.

**3-5.3.2 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, though at a slower rate than if no exhaust was provided (*see 3-5.2*). Table 3-4 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.

**3-6 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 will depend on the configuration of the smoke plume. Three smoke plume configurations are addressed in this guide.

**3-6.1 Axisymmetric Plumes.** An axisymmetric plume (*see Figure 3-6.1*) 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.

**3-6.1.1** The mass rate of smoke production can be estimated, based on the rate of entrained air, since the mass rate of combustion products generated from the fire is generally much less than the rate of air entrained in the plume.

**3-6.1.2** 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 204M, *Guide for Smoke and Heat Venting*. These relations were later slightly improved by incorporation of a virtual origin and also compared against other entrainment relations [2,15].

**Table 3-4 Increase in Time for Smoke Layer Interface to Reach Selected Position (Axisymmetric Plumes and Steady Fires)**

| | $t/t_0$ | | | | | |
|---|---|---|---|---|---|---|
| $m/m_e$ = | **0.25** | **0.35** | **0.50** | **0.70** | **0.85** | **0.95** |
| **z/H** | | | | | | |
| 0.2 | 1.12 | 1.19 | 1.30 | 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 | 1.40 | 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 |

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
$t_0$ = value of t in absence of smoke exhaust [*see Equation (9)*]
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 [from Equation (14)]

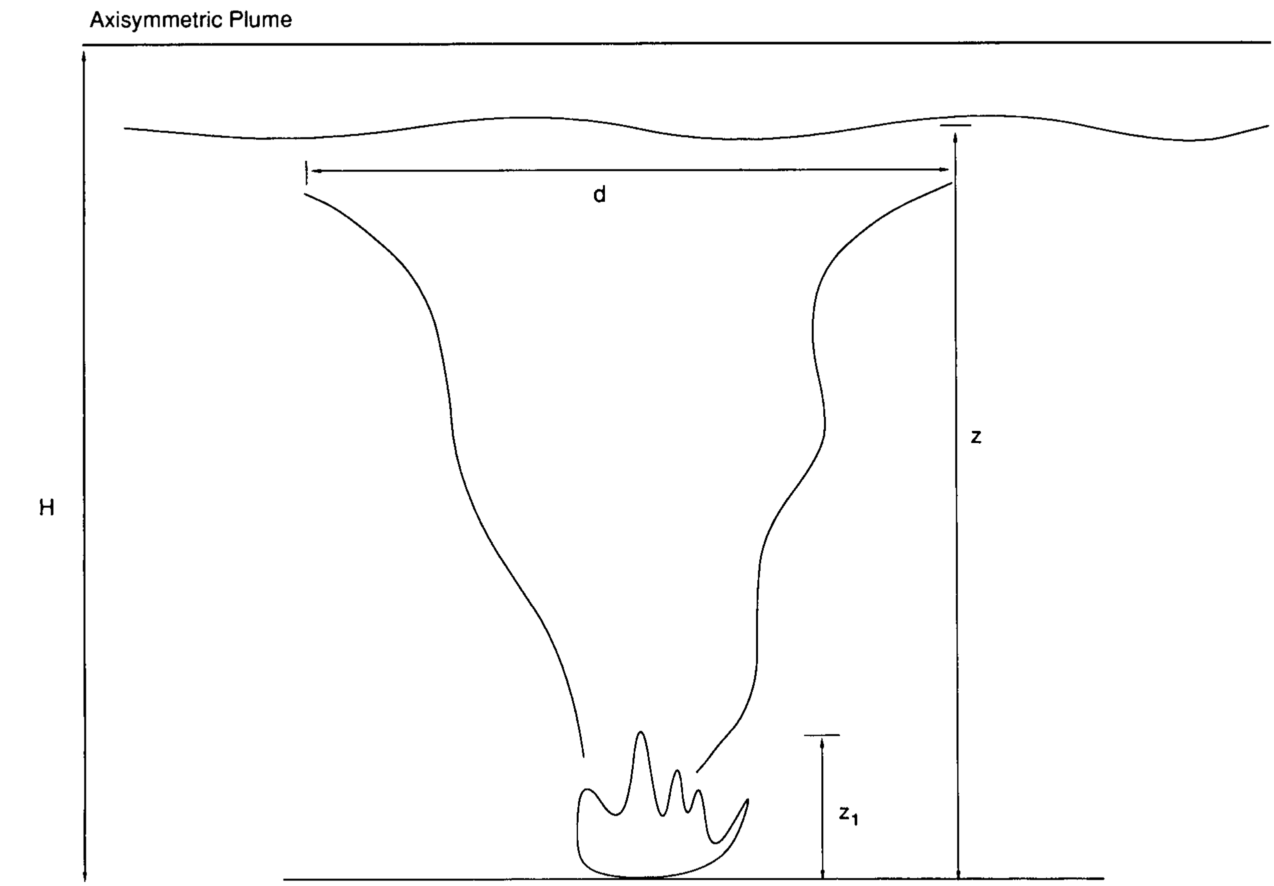


**Figure 3-6.1 Axisymmetric plume.**

(a) The following entrainment relations are essentially those presented in NFPA 204M [2]. Effects of virtual origin are ignored since 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:

$$z_l = 0.533\ Q_c^{2/5} \qquad (13)$$

where

$z_l$ = limiting elevation (ft)
$Q_c$ = convective portion of heat release rate (Btu/s)

(b) The plume mass flow rate, m, above the limiting elevation is predicted from:

$$m = 0.022\ Q_c^{1/3} z^{5/3} + 0.0042\ Q_c \qquad (z \geq z_l) \qquad (14)$$

where

m = mass flow rate in plume at height z (lb/s)
z = height above the fuel (ft)

(c) The plume mass flow rate below the flame tip is predicted from:

$$m = 0.0208\ Q_c^{3/5} z \qquad (z \geq z_l) \qquad (15)$$

**3-6.1.3** The rate of mass supplied by the plume to the smoke layer is obtained from Equation (15) for clear heights less than the flame height [*see Equation (13)*] and otherwise from Equation (14). The clear height is selected as the design height of the smoke layer interface above the fire source.

**3-6.1.4** It should be noted that Equations (14) and (15) 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 due to the amount of air entrained only being a function of the strength, i.e., rate of heat release, of the fire.

**3-6.1.5*** For practical reasons, expressing the smoke production rate in terms of a volumetric rate (cfm) may be preferred over a mass rate. This preference can be accommodated by dividing the mass flow rate by the density of smoke:

$$V = 60\ m/\rho \qquad (16)$$

where

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

**3-6.1.6** Fires may be located near the edge or a corner of the open space. In this case, entrainment may 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 assuming that entrainment occurs from all sides.

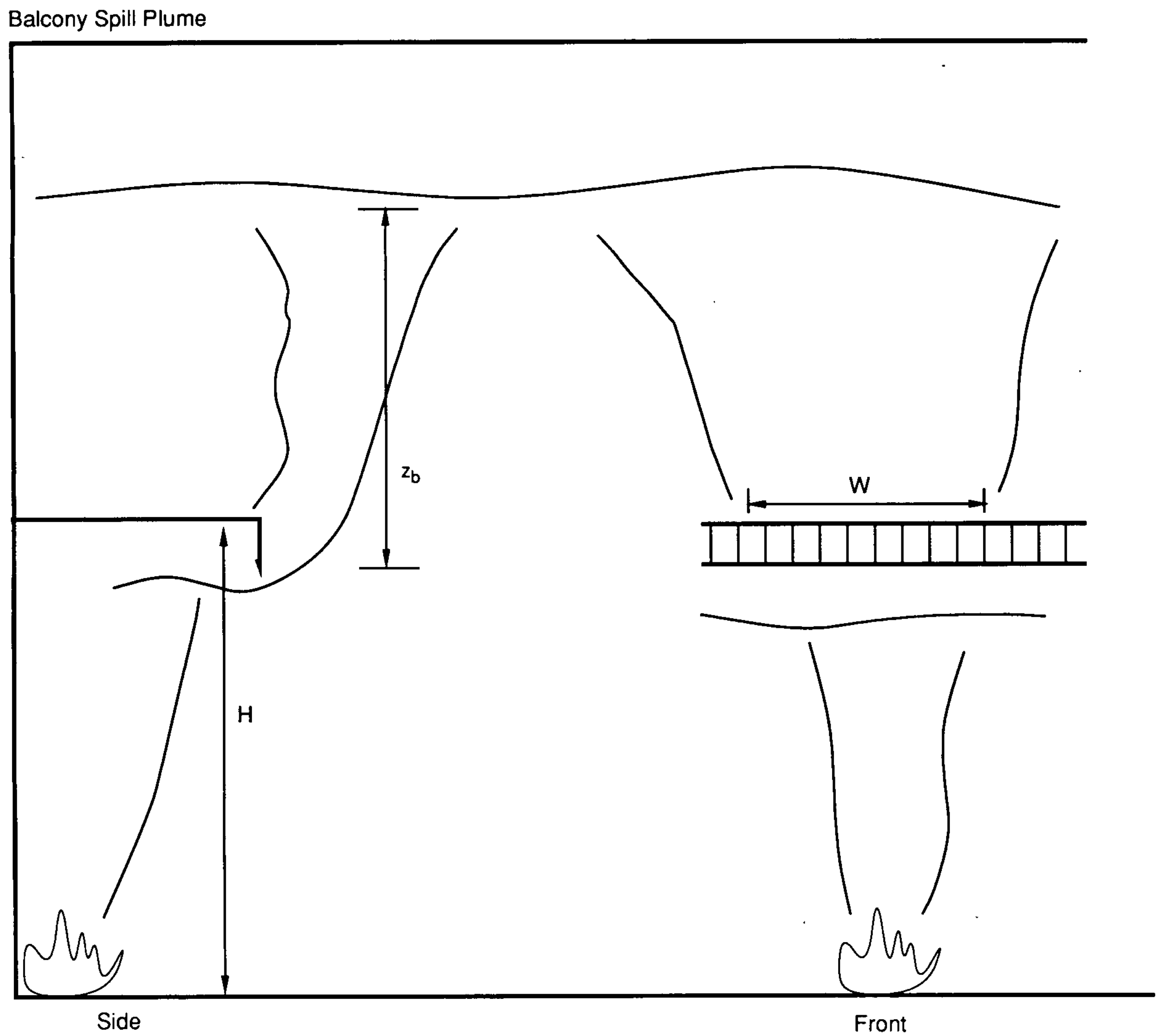


**Figure 3-6.2 Balcony spill plume.**

**3-6.2 Balcony Spill Plumes.**

**3-6.2.1** 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 3-6.2*). Air entrainment into balcony spill plumes can be calculated from Equation (17):

$$m = 0.124(QW^2)^{1/3}(Z_b + 0.3H)[1 + 0.063(Z_b + 0.6H)/W]^{2/3} \quad (17)$$

where

$m$ = mass flow rate in plume (lb/s)
$Q$ = heat release rate of the fire (Btu/s)
$W$ = 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)

This equation is based on Law's interpretation of data given by Morgan and Marshall, a subsequent reanalysis by Morgan, and modifications of a kind suggested by Thomas to make the calculated entrainment rate approach that for an axisymmetric plume at large heights [16,17,18,19]. Equation 17 should be regarded as an approximation to a complicated problem.

**3-6.2.2** 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.

**3-6.2.3** The rate of mass supplied by the plume to the smoke layer is obtained from Equation (17) by setting $Z_b$ equal to the height of the design smoke layer interface above the balcony.

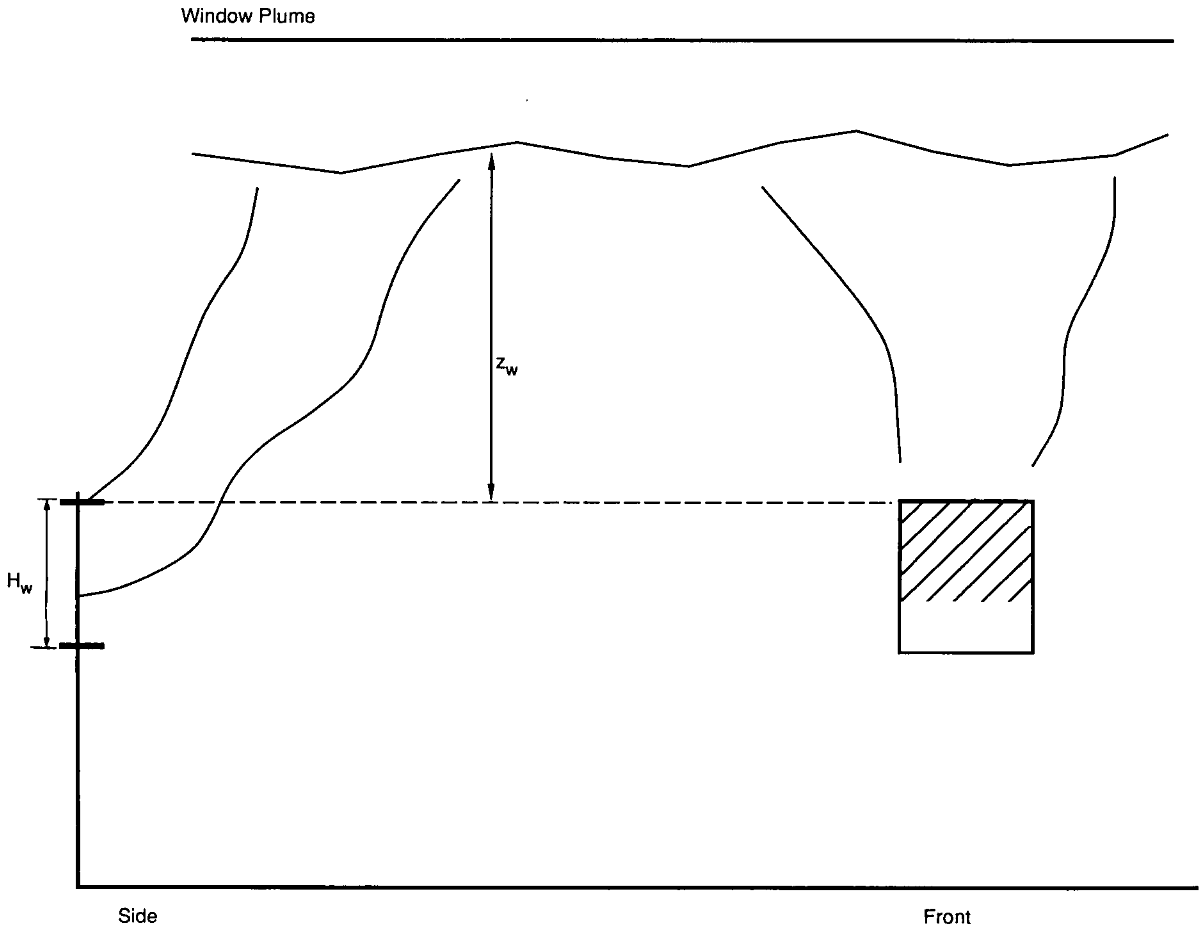


Figure 3-6.3 Window plume.

### 3-6.3 Window Plumes.

**3-6.3.1** Plumes issuing from wall openings, such as doors and windows, into a large volume open space are referred to as window plumes (*see Figure 3-6.3*). 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, i.e., 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 [20,21]:

$$Q = 61.2\ A_w\ H_w^{1/2} \qquad (18)$$

where

$Q$ = heat release rate (Btu/s)
$A_w$ = area of ventilation opening (ft$^2$)
$H_w$ = height of ventilation opening (ft)

**3-6.3.2** 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:

$$a = 2.40\ A_w^{2/5}\ H^{1/5} - 2.1\ H_w \qquad (19)$$

Then, the mass entrainment for window plumes is given as:

$$m = 0.022\ Q_c^{1/3}\ (z_w + a)^{5/3} + 0.0042\ Q_c \qquad (20)$$

where $z_w$ is the height above the top of the window.

Substituting for $Q_c$ from Equation (18),

$$m = 0.077\ (A_w\ H_w^{1/2})^{1/3}\ (z_w + a)^{5/3} + 0.18\ A_w\ H_w^{1/2} \quad (21)$$

**3-7 Influence of Plume Contact with Walls.** As a plume rises, it also widens. The plume may contact all of the walls of the open space prior to reaching the ceiling. In this case, the smoke interface will be considered to be at the height of contact with all of the surrounding walls. No additional smoke generation can be assumed above that point, as the entrainment is considered to be negligible above the point of contact. The overall plume diameter can be estimated as [15]:

$$d = 0.48\,[(T_0 + 460)/(T + 460)]^{1/2}\,Z \qquad (22)$$

where

d = plume diameter (based on excess temperature)(ft)
$T_0$ = temperature at plume centerline (°F)
T = ambient temperature (°F)
Z = height (ft)

In many cases near the top of an atrium, the plume centerline temperature will not be appreciably greater than ambient due to cooling caused by the entrainment of cool air along the entire length of the plume. Thus, generally the total plume diameter may be estimated as:

$$d = 0.5\,z \qquad (23)$$

**3-8 Maximum Air Supply Velocity.** The supply velocity of the makeup air at the perimeter of the large open space must 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 fpm (1 m/s) is recommended, based on flame deflection data [22].

**3-9 Temperature Rise in Smoke Layer.** The temperature of the upper layer is important in addressing concerns of tenability, as well as hardware requirements of exhaust fans.

The temperature rise can be determined using either Equation (24a) or (24b) as a basis.

$$\Delta T = Q_c / (mc) \qquad (24a)$$
$$\Delta T = 60\,Q_c / (\rho c V) \qquad (24b)$$

where

$\Delta T$ = temperature rise of smoke layer (°F)
$Q_c$ = convective portion of heat release rate (Btu/sec)
m = mass exhaust rate (lb/s)
V = volumetric venting rate (cfm)
c = specific heat of smoke at smoke layer temperature (Btu/lb-°F)
ρ = density of smoke at smoke layer temperature (lb/ft$^3$)

To adjust the volumetric venting rate for other heat release rates or temperature rises, the following equation may be applied:

$$[(T_2 + 460)\,V_1\,c_1\,\Delta T_1] / [(T + 460)\,V_2\,c_2\,\Delta T_2] = Q_{c1}/Q_{c2} \qquad (25)$$

where the variables are defined as in Equations (24a) and (24b) and:

T = temperature of smoke layer (°F)

subscripts:

1 = conditions associated with volumetric exhaust rate #1
2 = conditions associated with volumetric exhaust rate #2

Considering typical conditions anticipated in large volume spaces, the specific heat will not vary for the two exhaust rates. Thus, Equation (25) generally simplifies to:

$$[(T_2 + 460)/(T_1 + 460)]\,(V_1/V_2)(\Delta T_1/\Delta T_2) = Q_{c1}/Q_{c2} \qquad (26)$$

**3-10 Opposed Airflow Requirements.**

**3-10.1** 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 [23]:

$$v = 38\,[gH\,(T_f - T_0)/(T_f + 460)]^{1/2} \qquad (27)$$

where

v = air velocity (fpm)
g = acceleration of gravity (32.2 ft/s$^2$)
H = height of the opening (ft)
$T_f$ = temperature of heated smoke (°F)
$T_0$ = temperature of ambient air (°F)

For example, with H = 10 ft, $T_f$ = 165°F (considered realistic for sprinklered spaces) and $T_0$ = 70°F, the limiting velocity becomes 270 fpm. For the same conditions with $T_f$ = 1640°F (considered realistic for unsprinklered spaces), the limiting velocity becomes 594 fpm.

**3-10.2** 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 (28)]. 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:

$$v_e\,(\text{fpm}) = 17\,[Q/Z]^{1/3} \qquad (28)$$

where

$v_e$ = limiting average velocity (fpm)
Q = heat release rate of the fire (Btu/s)
Z = distance above the base of the fire to the bottom of the opening (ft). See Figure 3-10.2.

$v_e$ should not exceed 200 fpm. 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 (27) is used to calculate the limiting average velocity (setting $v = v_e$), where $T_f - T_0$ is the value of $\Delta T$ from Equation (24a) or Equation (24b) and $T_f = \Delta T + T_0$.

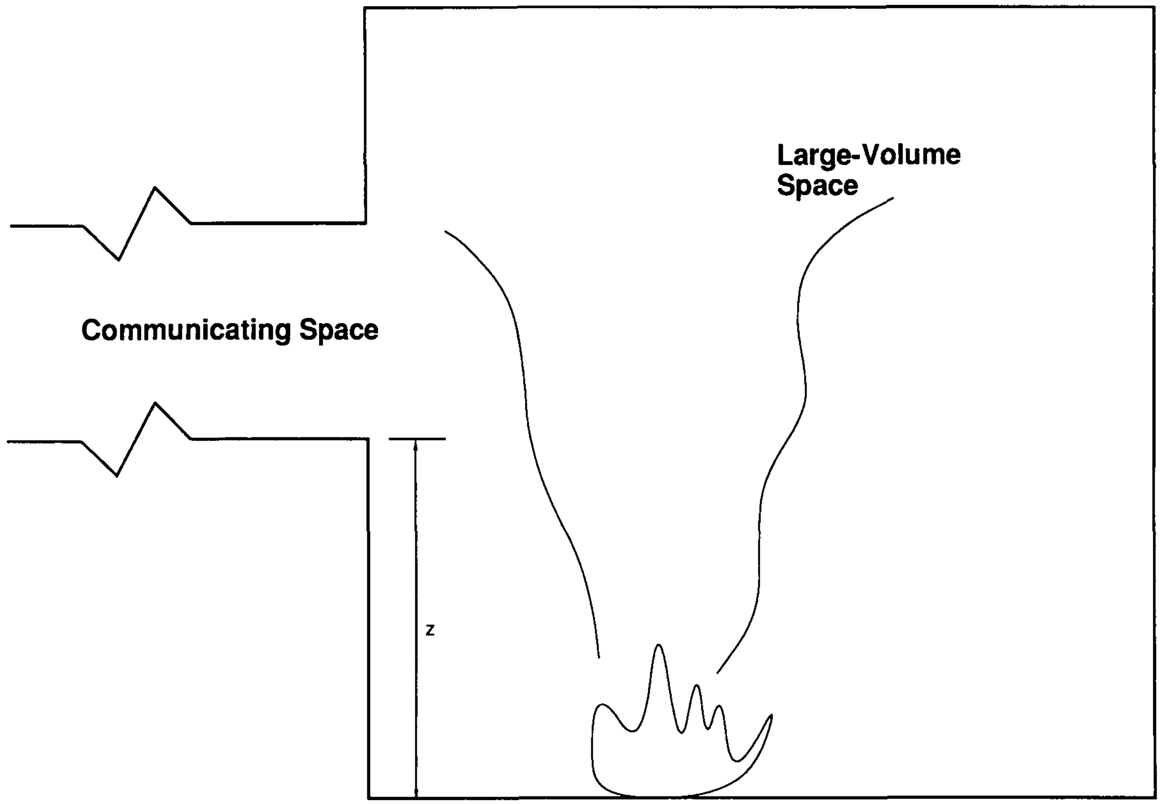


**Figure 3-10.2 Measurement of distance above base of fire to bottom of opening.**

# 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 must 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. While dilution with ambient air may significantly cool down the fire temperature, there may be instances where the direct effects of the fire will be 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 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 not practical, a powered supply system may be considered. This 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, may not be installed correctly, may not be properly tested, may have a low level of reliability, and may 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 must also be given to the stopping of operating equipment in proper sequence as 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 startup, 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 Supervision and Instrumentation.** Every system needs means of ensuring it will operate if needed. The means will vary according to the complexity and importance of the system. Supervision devices may include the following:

(a) End-to-end supervision of the wiring, equipment, and devices in a manner that includes provision for positive confirmation of activation, periodic testing, and manual override operation.

(b) Supervision of dedicated smoke management systems should include the presence of operating power downstream of all circuit disconnects.

(c) 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.

(d) 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.

(e) Other devices or means as appropriate.

**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** A protected power distribution and control circuit system should be considered. The threat to continuous power may be greater from an internal fire than from an interruption of an incoming utility line. These systems should be located in areas that would not be damaged from a fire in the large volume space.

**4-5.3** The probability of power outages and the significance of system failure to overall firesafety should be analyzed before requiring a separate standby power generating system.

**4-6 Materials.** Materials and equipment used for smoke management systems should conform to NFPA 90A, *Standard for the Installation of Air Conditioning and Ventilating Systems*, and other applicable NFPA documents.

**4-7 Other Building HVAC Systems.** When other systems in the building will be used as part of the smoke management system serving the large volume area, refer to NFPA 92A, *Recommended Practice for Smoke Control Systems*, 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 three categories:

(a) Component system testing

(b) Acceptance testing

(c) 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 and 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 will help overcome the numerous problems that occur during final acceptance testing and facilitate 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 General.** 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 clearly defined 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.

(a) Integrity of any partition, floor, or other member intended to resist smoke passage.

(b) Fire stopping.

(c) Doors and closers related to smoke control.

(d) 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 should be individually documented, including such items as speed, volume, sensitivity calibration, voltage, and amperage.

**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:

(a) Fire protective signaling system (*see NFPA 72H, Guide for Testing Procedures for Local, Auxiliary, Remote Station, and Proprietary Protective Signaling Systems*)

(b) Energy management system

(c) Building management system

(d) HVAC equipment

(e) Electrical equipment

(f) Temperature control system

(g) Power sources

(h) Standby power

(i) Automatic suppression systems

(j) Automatic operating doors and closures

(k) Other smoke control systems

(l) Emergency elevator operation.

**5-3 Acceptance Testing.**

**5-3.1** 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:

(a) Authority having jurisdiction

(b) Owner

(c) 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:

(a) Total volumetric flow rate

(b) Airflow velocities

(c) Airflow direction

(d) Door opening forces

(e) Pressure differentials

(f) Ambient temperature.

**5-3.3 Test Equipment.** The following equipment may be needed to perform acceptance testing:

(a) 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.

(b) Scale suitable for measuring door opening force.

(c) Anemometer, including traversing equipment.

(d) Ammeter.

(e) Door wedges.

(f) Tissue paper roll or other convenient device for indicating direction of airflow.

(g) Signs indicating that a test of the smoke management system is in progress and that doors should not be opened.

(h) Several walkie-talkie radios 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 following procedures:

**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:

(a) Normal mode

(b) Automatic smoke management mode for first alarm

(c) Manual override of normal and automatic smoke management modes

(d) 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 may 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 may 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 may come in many configurations, each of which has its own peculiarities. They may be tall and thin; 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 may 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, 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 General.** 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. But there are many valid reasons why such a fire is usually not practical in a completed building. Open flame/actual fire testing may 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 may 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 to evaluate 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. Since the owner may assume beneficial use of the smoke management system whenever there are 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 whenever 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 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:

(a) Across smoke barrier openings, and

(b) At the air makeup supplies, and

(c) 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 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 should also be conducted under standby power, if applicable.

**5-4.4** Special arrangements may 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 such unconditioned air might damage contents. Since smoke management systems may 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 part of the recommendations of this document. The edition indicated for each reference is the current edition as of the date of the NFPA issuance of this document.

**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*, 1990 edition

NFPA 71, *Standard for the Installation, Maintenance, and Use of Signaling Systems for Central Station Service*, 1989 edition

NFPA 72E, *Standard on Automatic Fire Detectors*, 1990 edition

NFPA 72H, *Guide for Testing Procedures for Local, Auxiliary, Remote Station, and Proprietary Protective Signalling Systems*, 1988 edition

NFPA 90A, *Standard for the Installation of Air Conditioning and Ventilating Systems*, 1989 edition

NFPA 92A, *Recommended Practice for Smoke Control Systems*, 1988 edition

NFPA *101, Life Safety Code*, 1991 edition

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

**6-1.2 UL Publications.** Underwriters Laboratories Inc., 333 Pfingsten Road, Northbrook, IL 60062.

UL 555-1990, *Standard for Fire Dampers*

UL 555S-1983, *Standard for Leakage Rated Dampers for Use in Smoke Control Systems*

## Appendix A

*This Appendix is not a part of the recommendations of this NFPA document, but is included for information purposes only.*

**A-1-2** This guide makes no differentiation in the technical approach to smoke management in atria and that in covered malls.

**A-1-6.3** Weather information for many North American and some overseas locations is presented in the ASHRAE *Handbook of Fundamentals*. Most weather data is collected at municipal airports or military installations, which may not be representative of weather at the location being considered. Also, extreme temperatures and wind velocities are not given. Those data need to be used with caution.

**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 U.K. 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-3-6.1.5** 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:

$$\rho/\rho^0 = 528/(460 + T)$$

where

$\rho^0$ = 0.075 (lb/ft$^3$)

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

T = temperature of smoke (°F)

**A-5-3.6.2 Real Fire Tests.** 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 Heat Release Rate Data

*This Appendix is not a part of the recommendations of this NFPA document, but is included for information purposes only.*

Heat release rate data provided in this appendix are included to assist users of this document in estimating the heat release rate of a design fire. The following figures and tables are extracted from numerous sources. Being from numerous sources, the cited units are not consistent throughout all of the figures and tables. However, the inconsistent units are provided in order to present the user with the exact tables from the original sources, rather than provide converted values that incorporate some round-off. The user may have to convert information from these tables into the form required by equations presented elsewhere in this document.

### Heat Release Rate

The burning rate of materials can be related to the heat release rate of materials by multiplying the mass loss rate by the effective heat of combustion of the fuel. These heat release rates are often given as an energy release rate per unit area of fuel. Figures B-1 and B-2 give heat release data for fuels burning in the open [24].

**Figure B-1 Unit Heat Release Rates for Fuels Burning in the Open**

| Commodity | Heat Release Rate (Btu/s) |
|---|---|
| Flammable liquid pool | 290/ft² of surface |
| Flammable liquid spray | 2,000/gpm of flow |
| Pallet stack | 1,000/ft of height |
| Wood or PMMA*(vertical) | |
| - 2-ft height | 30/ft of width |
| - 6-ft height | 70/ft of width |
| - 8-ft height | 180/ft of width |
| - 12-ft height | 300/ft of width |
| Wood or PMMA | |
| - Top of horizontal surface | 63/ft² of surface |
| Solid polystyrene (vertical) | |
| - 2-ft height | 63/ft of width |
| - 6-ft height | 130/ft of width |
| - 8-ft height | 400/ft of width |
| - 12-ft height | 680/ft of width |
| Solid polystyrene (horizontal) | 120/ft² of surface |
| Solid polypropylene (vertical) | |
| - 2-ft height | 63/ft of width |
| - 6-ft height | 100/ft of width |
| - 8-ft height | 280/ft of width |
| - 12- ft height | 470/ft of width |
| Solid polypropylene (horizontal) | 70/ft² of surface |

*PMMA, Polymethyl Methacrylate (Plexiglass, Lucite, acrylic)

**Figure B-2 Unit Heat Release Rate for Commodities**

Heat release rate per unit floor area of fully involved combustibles, based on negligible radiative feedback from the surroundings and 100% combustion efficiency.

| Commodity | Btu/s per ft² of Floor Area |
|---|---|
| 1. Wood pallets, stacked 1½ ft high (6-12% moisture) | 125 |
| 2. Wood pallets, stacked 5 ft high (6-12% moisture) | 350 |
| 3. Wood pallets, stacked 10 ft high (6-12% moisture) | 600 |
| 4. Wood pallets, stacked 16 ft high (6-12% moisture) | 900 |
| 5. Mail bags, filled, stored 5 ft high | 35 |
| 6. Cartons, compartmented, stacked 15 ft high | 150 |
| 7. PE letter trays, filled, stacked 5 ft high on cart | 750 |
| 8. PE trash barrels in cartons, stacked 15 ft high | 175 |
| 9. PE fiberglass shower stalls in cartons, stacked 15 ft high | 125 |
| 10. PE bottles packed in Item 6 | 550 |
| 11. PE bottles in cartons, stacked 15 ft high | 175 |
| 12. PU insulation board, rigid foam, stacked 15 ft high | 170 |
| 13. PS jars packed in Item 6 | 1,250 |
| 14. PS tubs nested in cartons, stacked 14 ft high | 475 |
| 15. PS toy parts in cartons, stacked 15 ft high | 180 |
| 16. PS insulation board, rigid foam, stacked 14 ft high | 290 |
| 17. PVC bottles packed in Item 6 | 300 |
| 18. PP tubs packed in Item 6 | 390 |
| 19. PP & PE film in rolls, stacked 14 ft high | 550 |
| 20. Methyl alcohol | 65 |
| 21. Gasoline | 290 |
| 22. Kerosene | 290 |
| 23. Diesel oil | 175 |

Note: PE = Polyethylene; PP = Polypropylene; PS = Polystyrene; PU = Polyurethane; PV = Polyvinyl chloride

**Table B-1 Maximum Heat Release Rates**

$$Q_m = qA$$

where

$Q_m$ = Maximum Heat Release Rate (Btu/sec)
$q$ = Heat Release Density (Btu/sec/ft²)
$A$ = Floor Area (ft²)

The following 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.)

**Warehouse Materials**

| | Growth Time (sec) | Heat Release Density(q) | Classification (s-slow) (m-medium) (f-fast) |
|---|---|---|---|
| 1. Wood pallets, stacked 1 ½ ft high (6-12% moisture) | 150-310 | 110 | m-f |
| 2. Wood pallets, stacked 5 ft high (6-12% moisture) | 90-190 | 330 | f |
| 3. Wood pallets, stacked 10 ft high (6-12% moisture) | 80-110 | 600 | f |
| 4. Wood pallets, stacked 16 ft high (6-12% moisture) | 75-105 | 900 | f |
| 5. Mail bags, filled, stored 5 ft high | 190 | 35 | f |
| 6. Cartons, compartmented, stacked 15 ft high | 60 | 200 | * |
| 7. Paper, vertical rolls, stacked 20 ft high | 15-28 | - | * |
| 8. Cotton (also PE, PE/Cot, Acrylic/Nylon/PE), garments in 12-ft high rack | 20-42 | - | * |

**Table B-4 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 mockups | 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 |

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

**Table B-5 Heat Release Rates of Chairs in Recent NBS Tests [3]**

| Specimen | Mass (kg) | Combustible (kg) | Style | Frame | Padding | Fabric | Interliner | Peak m (g/s) | 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] |
| 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(x4) | 2.6 | stacking chairs (4) | metal | PU | PVC | - | 7.2 | 160 |

[a] Estimated from mass loss records and assumed $Wh_c$
[b] Estimated from doorway gas concentrations
1 lb/s = 0.4536 kg/s = 453.6 g/s
1 lb = 0.4536 kg
1 Btu/s = 1.055 kW

**Warehouse Materials**

| | Growth Time (sec) | Heat Release Density(q) | Classification (s-slow) (m-medium) (f-fast) |
|---|---|---|---|
| 9. Cartons on pallets, rack storage, 15-30 ft high | 40-280 | – | m-f |
| 10. Paper products, densely packed in cartons, rack storage, 20 ft high | 470 | – | m-s |
| 11. PE letter trays, filled, stacked 5 ft high on cart | 190 | 750 | f |
| 12. PE trash barrels in cartons stacked 15 ft high | 55 | 250 | * |
| 13. FRP shower stalls in cartons, stacked 15 ft high | 85 | 110 | * |
| 14. PE bottles packed in Item 6 | 85 | 550 | * |
| 15. PE bottles in cartons, stacked 15 ft high | 75 | 170 | * |
| 16. PE pallets, stacked 3 ft high | 130 | – | f |
| 17. PE pallets, stacked 6-8 ft high | 30-55 | – | * |
| 18. PU mattress, single, horizontal | 110 | – | f |
| 19. PF insulation, board, rigid foam, stacked 15 ft high | 8 | 170 | * |
| 20. PS jars packed in Item 6 | 55 | 1200 | * |
| 21. PS tubs nested in cartons, stacked 14 ft high | 105 | 450 | f |
| 22. PS toy parts in cartons, stacked 15 ft high | 110 | 180 | f |
| 23. PS insulation board, rigid, stacked 14 ft high | 7 | 290 | * |
| 24. PVC bottles packed in Item 6 | 9 | 300 | * |
| 25. PP tubs packed in Item 6 | 10 | 390 | * |
| 26. PP and PE film in rolls, stacked 14 ft high | 40 | 350 | * |
| 27. Distilled spirits in barrels, stacked 20 ft high | 23-40 | – | * |
| 28. Methyl alcohol | – | 65 | – |
| 29. Gasoline | – | 200 | – |
| 30. Kerosene | – | 200 | – |
| 31. Diesel Oil | – | 180 | – |

* Fire growth rate exceeds classification criteria.
For SI Units: 1 ft = 0.305 m

**Table B-2 Maximum Heat Release Rates from Fire Detection Institute Analysis**

| | Approximate Values (Btu/sec) |
|---|---|
| 1. Medium wastebasket with milk cartons | 100 |
| 2. Large barrel with milk cartons | 140 |
| 3. Upholstered chair with polyurethane foam | 350 |
| 4. Latex foam mattress (heat at room door) | 1200 |
| 5. Furnished living room (heat at open door) | 4000-8000 |

**Table B-3 Characteristics of Ignition Sources [3]**

| | Typical Heat Output (w) | Burn Time[a] (s) | Maximum Flame Height (mm) | Flame Width (mm) | Maximum Heat Flux (kW/m²) |
|---|---|---|---|---|---|
| Cigarette 1.1 g (not puffed, laid on solid surface), bone dry, | 5 | 1200 | – | – | 42 |
| conditioned to 50% R.H. | 5 | 1200 | – | – | 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 | 1000 | 190 | | | 15[d] |
| No. 5 crib, 17 g | 1900 | 200 | | | 17[d] |
| No. 6 crib, 60 g | 2600 | 190 | | | 20[d] |
| No. 7 crib, 126 g | 6400 | 350 | | | 25[d] |
| Crumpled brown lunch bag, 6 g | 1200 | 80 | | | |
| Crumpled wax paper, 4.5 g (tight) | 1800 | 25 | | | |
| Crumpled wax paper, 4.5 g (loose) | 5300 | 20 | | | |
| Folded double-sheet newspaper, 22 g (bottom ignition) | 4000 | 100 | | | |
| Crumpled double-sheet newspaper, 22 g (top ignition) | 7400 | 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] | | | |

[a] Time duration of significant flaming.
[b] Total burn time in excess of 1800 s.
[c] As measured on simulation burner.
[d] Measured from 25 mm away.
[e] Results vary greatly with packing density.
1 in. = 25.4 mm
1 Btu/s = 1.055 W
1 oz = 0.02835 kg = 28.35 g
1 Btu/ft²-s = 11.35 kW/m²

**Table B-6 Effect of Fabric Type on Heat Release Rate in Table B-5 (within each group all other construction features were kept constant) [3]**

| Specimen | Full-Scale Peak q (kW) | Fabric | Padding |
|---|---|---|---|
| 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 |

1 lb/ft$^2$ = 48.83 g/m$^2$
1 oz/ft$^2$ = 305 g/m$^2$
1 Btu/s = 1.055 kW

**Table B-7 Effect of Padding Type on Maximum Heat Release Rate in Table B-5 (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$^2$) |

1 lb/ft$^2$ = 48.83 g/m$^2$
1 oz/ft$^2$ = 305 g/m$^2$
1 Btu/s = 1.055 kW

**Table B-8 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 |

1 lb = 0.4536 kg
1 Btu/s = 1.055 kW

**Table B-9 Considerations for Selecting Heat Release Rates for Design**

| **Constant Heat Release Rate Fires** | | |
|---|---|---|
| Theobald (industrial) | 260 kW/m$^2$ | (approx. 26 Btu/s-ft$^2$) |
| Law (offices) | 290 kW/m$^2$ | (approx. 29 Btu/s-ft$^2$) |
| Hansell & Morgan (hotel rooms) | 249 kW/m$^2$ | (approx. 25 Btu/s-ft$^2$) |

**Variable Heat Release Rate Fires**

| **NBSIR 88-3695 Fuel Configuration** | **Fire Growth Rate** |
|---|---|
| Computer Work Station | |
| 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 |

| **NBS Monograph 173 Fuel Commodity** | **Peak Heat Release (kW)** |
|---|---|
| Chairs | 80-2480 (< 10, metal frame) |
| Loveseats | 940-2890 (370, metal frame) |
| Sofa | 3120 |

## Appendix C T-Squared Fires

*This Appendix is not a part of the recommendations of this NFPA document, but is included for information 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:

| 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 seconds)

### 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 may or may 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-1 is abstracted from NFPA 204M, *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 may 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, extracted from Nelson, Harold E., *An Engineering Analysis of the Early Stages of Fire Development—The Fire at the DuPont Plaza Hotel and Casino*—December 31, 1986, Report NBSIR 87-3560, National Institute of Standards and Technology, Gaithersburg, Maryland, 1987, 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 further 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 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-3 relates the classes of t-squared fire growth curves to a selection of actual fuel arrays extracted from NFPA 204M, *Guide for Smoke and Heat Venting*. The individual arrays are also described in Appendix B.

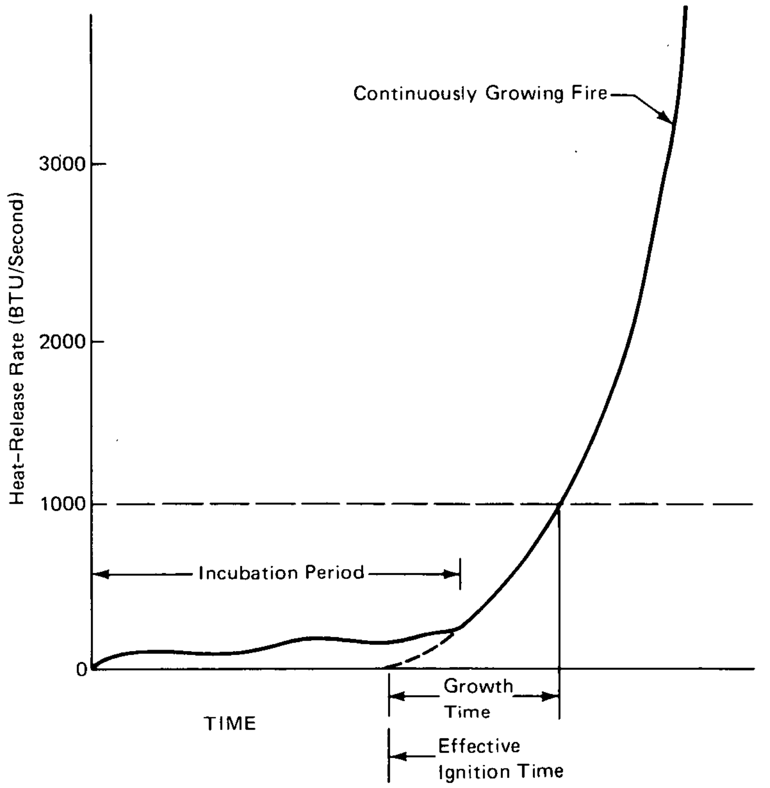


**Figure C-1 Conceptual illustration of contiuous fire growth.**

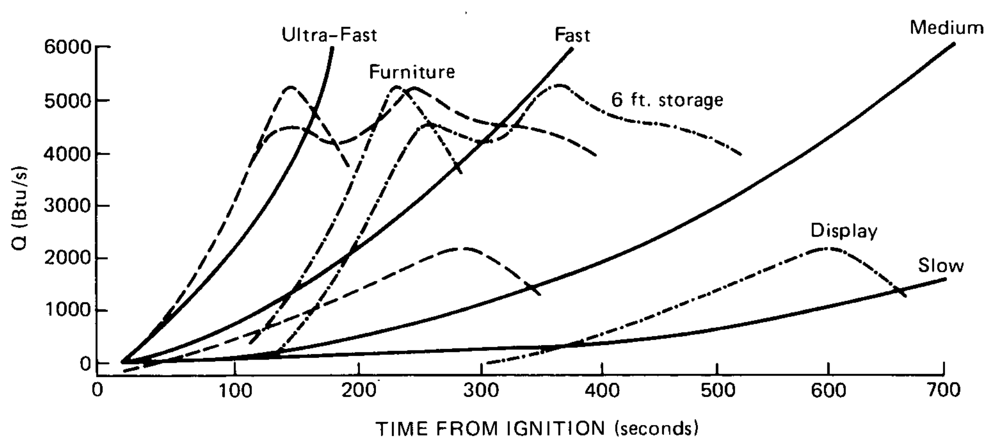


**Figure C-2 T-squared fire, rates of energy release.**

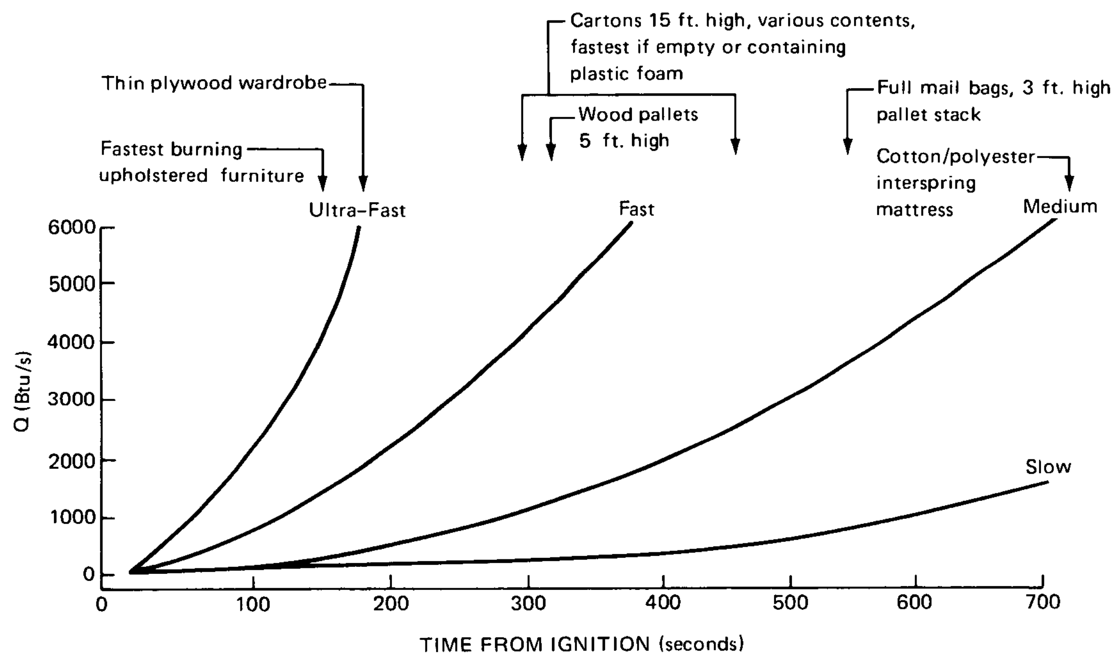


**Figure C-3 Relation of t-square fires to some fire tests.**

## 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 information purposes only.*

**Equation 1**

$R = [Q/(12\rho q'')]^{1/2}$

**Equation 2**

$Q = 1000\,(t/t_g)^2$

where

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

**Equation 3**

$X = 0.42\,Y^2 + 8.2 \times 10^{-8}\,Y^6$
for $X \leq 480$

where

$X = tQ^{1/3}/H^{4/3}$
$Y = \Delta T\,H^{5/3}/Q^{2/3}$

where

$t$ = time from ignition (s)
$Q$ = heat release rate (steady fire) (kW)
$H$ = ceiling height above the fire surface (m)
$\Delta T$ = temperature rise under the ceiling (°C)

**Equation 4**

$\Delta T = 2090\,[t/(t_g^{2/5}H^{4/5}) - 0.57]^{4/3}/\,[t_g^{4/5}H^{3/5}]$
($\Delta T$ in °C; $t$ and $t_g$ in s; $H$ in m)

**Equation 5**

$z_m = 5.54\,Q_c^{\,1/4}(dT/dz)^{-3/8}$

where

$z_m$ = maximum height of smoke rise above fire surface (m)
$Q_c$ = convective portion of the heat release rate (kW)
$dT/dz$ = rate of change of ambient temperature with respect to height (°C/m)

**Equation 6**

$Q_{c,min} = 1.18 \times 10^{-3}\,H^{5/2}\,\Delta T_0^{\,3/2}$

where

$Q_{c,min}$ = minimum convective heat release rate to overcome stratification (kW)
$H$ = ceiling height above fire surface (m)
$\Delta T_0$ = temperature change from fire surface to ceiling of open space (°C)

**Equation 7**

$\Delta T_0 = 96\,Q_c^{\,2/3}\,H^{-5/3}$

where

$\Delta T_0$ = temperature change from fire surface to ceiling of open space (°C)
$Q_c$ = convective portion of the heat release rate (kW)
$H$ = ceiling height above fire surface (m)

**Equation 8**

$H_{max} = 15.5\ Q_c^{2/5}\ \Delta T_0^{-3/5}$

where

$H$ = ceiling height above fire surface (m)
$Q_c$ = convective portion of the heat release rate (kW)
$\Delta T_0$ = temperature change from fire surface to ceiling of open space (°C)

**Equation 9**

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

where

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

**Equation 10**

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

see Equation (8) for nomenclature, and

$t_g$ = growth time (sec)

**Equation 11**

$m = Q\ \Delta t/H_c$

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 12**

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

see Equation (10) for nomenclature, and

$t_g$ = growth time (sec)

**Equation 13**

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

where

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

**Equation 14**

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

**Equation 15**

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

see Equation (14) for nomenclature

**Equation 16**

$V = m/\rho$

where

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

**Equation 17**

$m_p = 0.41\ (QW^2)^{1/3}\ (Z_b + 0.30H)\ [1 + 0.063\ (Z_b + 0.60H)/W]^{2/3}$

where

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

**Equation 18**

$Q = 1260\ A_W\ H_W^{1/2}$

where

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

**Equation 19**

$a = 2.40\ A_W^{2/5}\ H_W^{1/5} - 2.1\ H_W$

where

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

**Equation 20**

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

where

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

**Equation 21**

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

where

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

**Equation 22**

$d = 0.48\ (T_0/T)^{1/2}\ z$

where

$d$ = plume diameter (based on excess temperature) (m)
$T_0$ = temperatùre at plume centerline (K)
$T$ = ambient temperature (K)
$z$ = height (m)

**Equation 23**

$$d = 0.5\ z$$

see Equation (22) for nomenclature

**Equation 24a**

$$\Delta T = Q_c/mc$$

**Equation 24b**

$$\Delta T = Q_c/\rho cV$$

where

$\Delta T$ = temperature rise of smoke layer (K)
$Q_c$ = convective portion of heat release rate (kW)
m = mass exhaust rate (kg/s)
c = specific heat of smoke at smoke layer temperature (kJ/kg-K)
$\rho$ = density of smoke at smoke layer temperature (kg/m$^3$)
V = volumetric venting rate (m$^3$/s)

**Equation 25**

$$(T_2V_1c_1\Delta T_1)/(T_1V_2c_2\Delta T_2) = Q_{c1}/Q_{c2}$$

where

T = temperature of smoke layer (K)
V = volumetric venting rate (m$^3$/s)
c = specific heat of smoke at smoke layer temperature (kJ/kg-K)
$\Delta T$ = temperature rise of smoke layer (K)
$Q_c$ = convective portion of heat release rate (kW)
subscripts
1 = conditions associated with volumetric exhaust rate #1
2 = conditions associated with volumetric exhaust rate #2

**Equation 26**

$$(V_1/V_2)\ (\Delta T_1/\Delta T_2) = (Q_{c1}/Q_{c2})$$

where

V = volumetric venting rate (m$^3$/s)
T = temperature rise of smoke layer (K)
Q = heat release rate (kW)

**Equation 27**

$$v = 0.64\ [gH\ (T_f - T_0)/T_f]^{1/2}$$

where

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

**Equation 28**

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

where

$v_e$ = air velocity (m/s)
Q = heat release rate (kW)
z = distance above the base of the fire to the bottom of the opening (m)

## Appendix E

*This Appendix is not a part of the recommendations of this NFPA document, but is included for information purposes only.*

Example problems illustrating the use of the equations in NFPA 92B.

Given: Atrium with uniform rectangular cross-section.
Height: 120 ft
Horizontal dimensions: 100 ft × 200 ft
Normal temperature difference, floor to ceiling: 50°F
Design fire: 5,000 Btu/s

1. Determine activation times for:

(a) Spot smoke detector ($\Delta T$ = 18°F) located at the ceiling.

Using Equation (3) from 3-3.4 for steady fires, the activation time is given by t, included in the factor, X.

First, evaluate Y:

$$Y = \Delta T H^{5/3} Q^{2/3}$$
$$Y = (18)\ (120)^{5/3}/(5000)^{2/3}$$
$$Y = 179.7$$

Solving for X:

$$X = 4.6 \times 10^{-4}\ Y^2 + 2.7 \times 10^{-15}\ Y^6$$
$$X = 4.6 \times 10^{-4}\ (179.7)^2 + 2.7 \times 10^{-15}\ (179.7)^6$$
$$X = 14.94$$

Determine t:

$$X = t\ Q^{1/3}/H^{4/3}$$
$$14.94 = t\ (5000)^{1/3}/(120)^{4/3}$$
$$14.94 = t\ (17.1)/591.9$$
$$t = 517 \text{ sec or } 8.6 \text{ min}$$

(b) Sprinkler ($\Delta T$ = 144°F) located at the ceiling

As in the case shown above, use Equation (3) from 3-3.4.

Evaluate Y:

$$Y = \Delta T H^{5/3}/Q^{2/3}$$
$$Y = (144)\ (120)^{5/3}/(5000)^{2/3}$$
$$Y = 1437.8$$

Solving for X:

$$X = 4.6 \times 10^{-4}\ Y^2 + 2.7 \times 10^{-15}\ Y^6$$
$$X = 4.6 \times 10^{-4}\ (1437.8)^2 + 2.7 \times 10^{-15}\ (179.7)^6$$
$$X = 24{,}804$$

Determine t:

$$X = t\ Q^{1/3}/H^{4/3}$$
$$24{,}804 = t\ (5000)^{1/3}/(120)^{4/3}$$
$$24{,}804 = t\ (17.1)/591.9$$
$$t = 855{,}000 \text{ sec}$$

2. Is the smoke likely to stratify prior to reaching the ceiling?

The analysis of ceiling-mounted detectors is valid only if the smoke reaches the ceiling. This question poses as a check.

Using Equation (8) from Section 3-4:

$H_{max} = 74\ Q_c^{2/5}\ \Delta T_0^{-3/5}$
$H_{max} = 74\ (5000 \bullet 0.7)^{2/5}\ (50)^{-3/5}$
$H_{max} = 74\ (26.2)\ (0.096)$
$H_{max} = 186$ ft

Since $H_{max}$ is greater than the ceiling height, the smoke is likely to reach the ceiling and not stratify prematurely. Thus, the analysis in Question #1 was appropriate.

3. From #1, what is the smoke layer depth when the smoke detector activates?

A hazard analysis must consider if the smoke management system actuates prior to the onset of hazardous conditions. The depth of the smoke layer can be determined using Equation (9) of 3-5.2 for steady fires:

Given:

H = 120 ft
t = 517 sec for smoke detector
Q = 5000 Btu/s
A = 100 ft × 200 ft = 20,000 $ft^2$

$z/H = 0.67 - 0.28 \ln [(tQ^{1/3}/H^{4/3})/(A/H^2)]$
$z/H = 0.67 - 0.28 \ln [(517 \bullet 5000^{1/3}/120^{4/3})/(20{,}000/120^2)]$
$z/H = 0.67 - 0.28 \ln [10.75]$
$z/H = 0.0055$

Therefore, z = 0.66 ft

NOTE: The smoke layer is determined to have descended almost to fire at the time of detection. Thus, detection is considered to be too slow for the purpose of this example.

Alternatively, try t = 120 sec, associated with a means of detection with a reduced time to activation, e.g., beam detection.

$z/H = 0.67 - 0.28 \ln [(120 \bullet 5000^{1/3}/120^{4/3})/(20{,}000/120^2)]$
$z/H = 0.67 - 0.28 \ln [(120 \bullet 17.1/592)/(20{,}000/14{,}400)]$
$z/H = 0.67 - 0.28 \ln [2.493]$
$z/H = 0.41$

Therefore, z = 49.2 ft

4. Determine the volumetric exhaust rate required to keep smoke 5 ft above the highest walking level in the atrium, i.e., 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 (13) of 3-6.1 must be applied to determine the flame height.

Given:

$Q_c = 3500$ Btu/s
$z_l = 0.533\ Q_c^{2/5}$
$z_l = 0.533\ (3500)^{2/5}$
$z_l = 13.9$ 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 (14) 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/s

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 using Equation (16) from 3-6.1:

$V = m/\rho$ where $\rho = 0.075$ lb/$ft^3$
V = 564/0.075
V = 7521 $ft^3$/s or 451,260 scfm

5. Determine if the plume will contact all of the walls prior to reaching the design height noted in #4 (5 ft above the highest walking level).

The above calculation in #4 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 (23) (Section 3-7) 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.

6. Determine the temperature of the smoke layer after fan actuation.

The quality of the smoke contained in the smoke layer may be important in the context of tenability or damageability studies. Applying Equation (24a) from Section 3-9:

Given:

$Q_c = 3500$ Btu/s
m = 564 lb/s
c = 0.24 Btu/lb-°F
$\Delta T = Q_c/mc$
$\Delta T = 3500/[(564)(0.24)]$
$\Delta T = 26$°F

7. 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 (27), Section 3-10:

Given:

H = 6 ft
g = 32.2 ft/$s^2$
$T_f = 1000$°F
$T_0 = 70$°F
$V = 38.4\ [gH\ (T_f - T_0)/(T_f + 460)]^{1/2}$
$V = 38.4\ [(32.2)(6)(1000 - 70)/(1000 + 460)]^{1/2}$
V = 426 fpm

(b) For a fire in the atrium, determine the opposed airflow required to restrict smoke spread into the tenant space.

Given:

$Q = 5000$ Btu/s
$z = 90$ ft
$V_e = 7\ [Q / z]^{1/3}$
$V_e = 17\ [5000/90]^{1/3}$
$V_e = 64.8$ fpm

## Appendix F Tables Illustrating Application of Selected Equations in Chapter 3.

**Equation 1. Separation Distance Required to Prevent Ignition (feet)**

| Ignition Flux | Heat Release Rate (Btu/s) | | | | |
|---|---|---|---|---|---|
| ($Btu/ft^2$-s) | 1000 | 2000 | 4000 | 8000 | 16,000 |
| 0.88 | 5.5 | 7.7 | 10.9 | 15.5 | 21.9 |
| 1.76 | 3.9 | 5.5 | 7.7 | 10.9 | 15.5 |
| 3.52 | 2.7 | 3.9 | 5.5 | 7.7 | 10.9 |

**Equation 3. Time from Ignition Before Detection (minutes)**

Detection Device - Smoke Detector ($\Delta T$ = 18°F)

| Clear Height (ft) | Total Heat Release Rate (Btu/s) 1000 | 2000 | 4000 | 8000 | 16,000 |
|---|---|---|---|---|---|
| 30 | 0 | 0 | 0 | 0 | 0 |
| 60 | 5 | 2 | 0 | 0 | 0 |
| 90 | 35 | 11 | 3 | 1 | 0 |
| 120 | 187 | 43 | 13 | 4 | 1 |
| 150 | No Det. | 151 | 38 | 11 | 4 |
| 180 | No Det. | 562 | 98 | 27 | 8 |
| 210 | No Det. | No Det. | 256 | 58 | 17 |
| 240 | No Det. | No Det. | 706 | 120 | 33 |
| 270 | No Det. | No Det. | No Det. | 248 | 59 |
| 300 | No Det. | No Det. | No Det. | 526 | 102 |

Detection Device - Sprinkler ($\Delta T$ = 144°F)

| Clear Height (ft) | Total Heat Release Rate (Btu/s) 1000 | 2000 | 4000 | 8000 | 16,000 |
|---|---|---|---|---|---|
| 30 | 15 | 4 | 1 | 0 | 0 |
| 60 | No Det. | 399 | 46 | 1 | 3 |
| 90 | No Det. | No Det. | No Det. | 139 | 24 |
| 120 | No Det. | No Det. | No Det. | No Det. | 175 |
| 150 | No Det. | No Det. | No Det. | No Det. | No Det. |
| 180 | No Det. | No Det. | No Det. | No Det. | No Det. |
| 210 | No Det. | No Det. | No Det. | No Det. | No Det. |
| 240 | No Det. | No Det. | No Det. | No Det. | No Det. |
| 270 | No Det. | No Det. | No Det. | No Det. | No Det. |
| 300 | No Det. | No Det. | No Det. | No Det. | No Det. |

**Equation 6. Heat Release Rate to Overcome Stratification (Btu/s) Temperature Change (°F)**

| Height (ft) | 10 | 20 | 30 | 40 | 50 |
|---|---|---|---|---|---|
| 30 | 3.7 | 10.5 | 19.4 | 29.8 | 41.7 |
| 60 | 21.1 | 59.6 | 109.5 | 168.6 | 235.6 |
| 90 | 58.1 | 164.3 | 301.8 | 464.6 | 649.3 |
| 120 | 119.2 | 337.2 | 619.5 | 953.8 | 1332.9 |
| 150 | 208.3 | 589.1 | 1082.2 | 1666.2 | 2328.5 |
| 180 | 328.5 | 929.2 | 1707.1 | 2628.3 | 3673.1 |
| 210 | 483.0 | 1366.1 | 2509.7 | 3864.0 | 5400.1 |
| 240 | 674.4 | 1907.5 | 3504.4 | 5395.3 | 7540.2 |
| 300 | 1178.2 | 3332.3 | 6121.9 | 9425.2 | 13172.1 |

**Equation 8. Maximum Ceiling Height without Stratification (ft) Heat Release Rate (Btu/sec)**

| Temperature Change (°F) | 1000 | 2000 | 4000 | 8000 | 16,000 |
|---|---|---|---|---|---|
| 10 | 255.4 | 337.0 | 444.7 | 586.8 | 774.3 |
| 20 | 168.5 | 222.4 | 293.4 | 387.2 | 510.9 |
| 30 | 132.1 | 174.3 | 230.0 | 303.6 | 400.5 |
| 40 | 111.2 | 146.7 | 193.6 | 255.4 | 337.0 |
| 50 | 97.2 | 128.3 | 169.3 | 223.4 | 294.8 |

**Equation 9. Height of Smoke Layer above Fire Surface (ft)**

| | | $A/H^2 = 1$ Total Heat Release Rate (Btu/s) | | | | |
|---|---|---|---|---|---|---|
| Time (min) | Height of Atrium (ft) | 1000 | 2000 | 4000 | 8000 | 16,000 |
| 2 | 30 | CF | CF | CF | CF | CF |
| 2 | 60 | 13 | 9 | 5 | 1 | CF |
| 2 | 90 | 33 | 27 | 21 | 15 | 10 |
| 2 | 120 | 57 | 49 | 41 | 33 | 26 |
| 2 | 150 | 83 | 74 | 64 | 54 | 45 |
| 2 | 180 | 112 | 101 | 89 | 77 | 66 |
| 2 | 210 | 143 | 129 | 116 | 102 | 89 |
| 2 | 240 | 175 | 160 | 144 | 129 | 113 |
| 2 | 270 | 209 | 192 | 174 | 157 | 139 |
| 2 | 300 | 244 | 225 | 206 | 186 | 167 |

| | | Total Heat Release Rate (Btu/s) | | | | |
|---|---|---|---|---|---|---|
| Time (min) | Height of Atrium (ft) | 1000 | 2000 | 4000 | 8000 | 16,000 |
| 5 | 30 | CF | CF | CF | CF | CF |
| 5 | 60 | CF | CF | CF | CF | CF |
| 5 | 90 | 10 | 4 | CF | CF | CF |
| 5 | 120 | 26 | 18 | 10 | 3 | CF |
| 5 | 150 | 45 | 35 | 25 | 16 | 6 |
| 5 | 180 | 66 | 54 | 43 | 31 | 20 |
| 5 | 210 | 89 | 76 | 62 | 48 | 35 |
| 5 | 240 | 114 | 98 | 83 | 67 | 52 |
| 5 | 270 | 140 | 123 | 105 | 88 | 70 |
| 5 | 300 | 167 | 148 | 129 | 109 | 90 |

| | | $A/H^2 = 10$ Total Heat Release Rate (Btu/s) | | | | |
|---|---|---|---|---|---|---|
| Time (min) | Height of Atrium (ft) | 1000 | 2000 | 4000 | 8000 | 16,000 |
| 2 | 30 | 18 | 16 | 14 | 12 | 10 |
| 2 | 60 | 51 | 48 | 44 | 40 | 36 |
| 2 | 90 | NL | 85 | 79 | 73 | 68 |
| 2 | 120 | NL | NL | 119 | 111 | 103 |
| 2 | 150 | NL | NL | NL | NL | 141 |
| 2 | 180 | NL | NL | NL | NL | NL |
| 2 | 210 | NL | NL | NL | NL | NL |
| 2 | 240 | NL | NL | NL | NL | NL |
| 2 | 270 | NL | NL | NL | NL | NL |
| 2 | 300 | NL | NL | NL | NL | NL |

| | | Total Heat Release Rate (Btu/s) | | | | |
|---|---|---|---|---|---|---|
| Time (min) | Height of Atrium (ft) | 1000 | 2000 | 4000 | 8000 | 16,000 |
| 5 | 30 | 10 | 8 | 6 | 4 | 3 |
| 5 | 60 | 36 | 32 | 28 | 24 | 21 |
| 5 | 90 | 68 | 62 | 56 | 50 | 45 |
| 5 | 120 | 103 | 96 | 88 | 80 | 72 |
| 5 | 150 | 142 | 132 | 122 | 112 | 103 |
| 5 | 180 | NL | 170 | 159 | 147 | 136 |
| 5 | 210 | NL | NL | 197 | 184 | 170 |
| 5 | 240 | NL | NL | 238 | 222 | 207 |
| 5 | 270 | NL | NL | NL | 262 | 244 |
| 5 | 300 | NL | NL | NL | NL | 283 |

NL = No smoke layer has begun to form.
CF = Atrium has completely filled with smoke.

**Equation 14. Volumetric Rate of Smoke Production (scfm)**
**Axisymmetric Plumes Total Heat Release Rates (Btu/s)**

| Clear Height (ft) | 1000 | 2000 | 4000 | 8000 | 16,000 |
|---|---|---|---|---|---|
| 30 | 47,557 | 61,637 | 81,106 | 109,096 | 151,285 |
| 60 | 145,926 | 185,545 | 237,185 | 305,697 | 398,930 |
| 90 | 284,603 | 360,227 | 457,219 | 582,859 | 748,052 |
| 120 | 458,299 | 579,021 | 732,818 | 930,012 | 1,185,335 |
| 150 | 663,756 | 837,821 | 1,058,810 | 1,340,641 | 1,702,576 |
| 180 | 898,674 | 1,133,730 | 1,431,546 | 1,810,151 | 2,293,985 |
| 210 | 1,161,305 | 1,464,547 | 1,848,254 | 2,335,048 | 2,955,161 |
| 240 | 1,450,254 | 1,828,516 | 2,306,720 | 2,912,546 | 3,682,594 |
| 270 | 1,764,372 | 2,224,190 | 2,805,122 | 3,540,348 | 4,473,393 |
| 300 | 2,102,690 | 2,650,344 | 3,341,919 | 4,216,514 | 5,325,111 |

| | Wall Plumes Total Heat Release Rate (Btu/s) | | | | |
|---|---|---|---|---|---|
| Clear Height (ft) | 1000 | 2000 | 4000 | 8000 | 16,000 |
| 30 | 30,818 | 40,553 | 54,548 | 75,642 | 109,146 |
| 60 | 92,773 | 118,592 | 152,849 | 199,465 | 265,116 |
| 90 | 180,114 | 228,610 | 291,430 | 374,026 | 484,999 |
| 120 | 289,510 | 366,409 | 465,006 | 592,668 | 760,406 |
| 150 | 418,910 | 529,405 | 670,321 | 851,288 | 1,086,172 |
| 180 | 566,865 | 715,773 | 905,076 | 1,146,993 | 1,458,651 |
| 210 | 732,274 | 924,127 | 1,167,524 | 1,477,580 | 1,875,069 |
| 240 | 914,258 | 1,153,360 | 1,456,273 | 1,841,297 | 2,333,218 |
| 270 | 1,112,095 | 1,402,561 | 1,770,174 | 2,236,696 | 2,831,274 |
| 300 | 1,325,172 | 1,670,959 | 2,108,257 | 2,662,556 | 3,367,699 |

| | Corner Plumes Total Heat Release Rate (Btu/s) | | | | |
|---|---|---|---|---|---|
| Clear Height (ft) | 1000 | 2000 | 4000 | 8000 | 16,000 |
| 30 | 20,276 | 27,274 | 37,821 | 54,573 | 82,606 |
| 60 | 59,296 | 76,424 | 99,732 | 132,558 | 180,839 |
| 90 | 114,305 | 145,715 | 187,013 | 242,499 | 319,324 |
| 120 | 183,205 | 232,503 | 296,334 | 380,203 | 492,780 |
| 150 | 264,702 | 335,160 | 425,644 | 543,086 | 697,952 |
| 180 | 357,887 | 452,538 | 573,496 | 729,325 | 932,544 |
| 210 | 462,063 | 583,762 | 738,790 | 937,535 | 1,194,811 |
| 240 | 576,680 | 728,136 | 920,649 | 1,166,609 | 1,483,360 |
| 270 | 701,280 | 885,087 | 1,118,348 | 1,415,637 | 1,797,043 |
| 300 | 835,480 | 1,054,128 | 1,331,278 | 1,683,850 | 2,134,892 |

**Equation 17. Volumetric Rate of Smoke Production (scfm)
Balcony Spill Plume**

| Plume Width (ft) | Height above Balcony (ft) | Total Heat Release Rate (Btu/s) 1000 | 2000 | 4000 | 8000 | 16,000 |
|---|---|---|---|---|---|---|
| 5 | 30 | 122,431 | 154,217 | 194,257 | 244,692 | 308,221 |
| 5 | 60 | 272,693 | 343,493 | 432,673 | 545,008 | 686,509 |
| 5 | 90 | 456,211 | 574,657 | 723,855 | 911,790 | 1,148,518 |
| 5 | 120 | 670,399 | 844,454 | 1,063,700 | 1,339,868 | 1,687,738 |
| 5 | 150 | 913,306 | 1,150,427 | 1,449,113 | 1,825,346 | 2,299,260 |
| 5 | 180 | 1,183,390 | 1,490,633 | 1,877,646 | 2,365,139 | 2,979,200 |
| 5 | 210 | 1,479,388 | 1,863,481 | 2,347,297 | 2,956,725 | 3,724,380 |
| 5 | 240 | 1,800,241 | 2,267,637 | 2,856,384 | 3,597,986 | 4,532,131 |
| 5 | 270 | 2,145,041 | 2,701,958 | 3,403,467 | 4,287,109 | 5,400,171 |
| 5 | 300 | 2,512,999 | 3,165,449 | 3,987,295 | 5,022,516 | 6,326,511 |

| Plume Width (ft) | Height above Balcony (ft) | Total Heat Release Rate (Btu/s) 1000 | 2000 | 4000 | 8000 | 16,000 |
|---|---|---|---|---|---|---|
| 10 | 30 | 173,475 | 218,515 | 275,248 | 346,710 | 436,727 |
| 10 | 60 | 364,393 | 459,001 | 578,171 | 728,282 | 917,366 |
| 10 | 90 | 584,804 | 736,637 | 927,890 | 1,168,798 | 1,472,253 |
| 10 | 120 | 833,075 | 1,049,366 | 1,321,813 | 1,664,995 | 2,097,278 |
| 10 | 150 | 1,107,868 | 1,395,504 | 1,757,819 | 2,214,201 | 2,789,074 |
| 10 | 180 | 1,408,061 | 1,773,636 | 2,234,125 | 2,814,171 | 3,544,815 |
| 10 | 210 | 1,732,694 | 2,182,553 | 2,749,209 | 3,462,986 | 4,362,081 |
| 10 | 240 | 2,080,930 | 2,621,202 | 3,301,745 | 4,158,977 | 5,238,772 |
| 10 | 270 | 2,452,037 | 3,088,660 | 3,890,568 | 4,900,676 | 6,173,039 |
| 10 | 300 | 2,845,361 | 3,584,102 | 4,514,643 | 5,686,779 | 7,163,238 |

| Plume Width (ft) | Height above Balcony (ft) | Total Heat Release Rate (Btu/s) 1000 | 2000 | 4000 | 8000 | 16,000 |
|---|---|---|---|---|---|---|
| 15 | 30 | 217,816 | 274,368 | 345,602 | 435,330 | 548,355 |
| 15 | 60 | 445,660 | 561,367 | 707,114 | 890,702 | 1,121,956 |
| 15 | 90 | 700,487 | 882,355 | 1,111,440 | 1,400,004 | 1,763,486 |
| 15 | 120 | 981,141 | 1,235,874 | 1,556,744 | 1,960,922 | 2,470,036 |
| 15 | 150 | 1,286,628 | 1,620,676 | 2,041,452 | 2,571,474 | 3,239,106 |
| 15 | 180 | 1,616,088 | 2,035,672 | 2,564,194 | 3,229,936 | 4,068,524 |
| 15 | 210 | 1,968,758 | 2,479,907 | 3,123,765 | 3,934,788 | 4,956,377 |
| 15 | 240 | 2,343,964 | 2,952,527 | 3,719,091 | 4,684,679 | 5,900,962 |
| 15 | 270 | 2,741,097 | 3,452,768 | 4,349,210 | 5,478,396 | 6,900,752 |
| 15 | 300 | 3,159,610 | 3,979,940 | 5,013,252 | 6,314,842 | 7,954,364 |

| Plume Width (ft) | Height above Balcony (ft) | Total Heat Release Rate (Btu/s) 1000 | 2000 | 4000 | 8000 | 16,000 |
|---|---|---|---|---|---|---|
| 20 | 30 | 258,005 | 324,991 | 409,368 | 515,652 | 649,531 |
| 20 | 60 | 520,059 | 655,082 | 825,161 | 1,039,398 | 1,309,257 |
| 20 | 90 | 807,263 | 1,016,853 | 1,280,858 | 1,613,407 | 2,032,296 |
| 20 | 120 | 1,118,737 | 1,409,195 | 1,775,064 | 2,235,924 | 2,816,437 |
| 20 | 150 | 1,453,705 | 1,831,131 | 2,306,547 | 2,905,396 | 3,659,724 |
| 20 | 180 | 1,811,476 | 2,281,790 | 2,874,211 | 3,620,443 | 4,560,418 |
| 20 | 210 | 2,191,430 | 2,760,390 | 3,477,070 | 4,379,822 | 5,516,955 |
| 20 | 240 | 2,593,002 | 3,266,223 | 4,114,233 | 5,182,411 | 6,527,921 |
| 20 | 270 | 3,015,683 | 3,798,645 | 4,784,887 | 6,027,187 | 7,592,025 |
| 20 | 300 | 3,459,003 | 4,357,063 | 5,488,288 | 6,913,212 | 8,708,089 |

**Equation 21. Volumetric Rate of Smoke Production Window Plumes (scfm)**

| Window Height (ft) | Height above Top of Window (ft) | Area of Window (ft²) 10 | 50 | 100 |
|---|---|---|---|---|
| 5 | 30 | 47,544 | 128,964 | 209,894 |
| 5 | 60 | 153,297 | 330,552 | 480,731 |
| 5 | 90 | 304,459 | 606,468 | 842,788 |
| 5 | 120 | 494,883 | 947,631 | 1,285,598 |
| 5 | 150 | 720,838 | 1,348,265 | 1,802,326 |
| 5 | 180 | 979,710 | 1,804,224 | 2,387,998 |
| 5 | 210 | 1,269,519 | 2,312,329 | 3,038,765 |
| 5 | 240 | 1,588,691 | 2,870,025 | 3,751,515 |
| 5 | 270 | 1,935,933 | 3,475,197 | 4,523,660 |
| 5 | 300 | 2,310,152 | 4,126,051 | 5,352,999 |

| Window Height (ft) | Height above Top of Window (ft) | Area of Window (ft²) 10 | 50 | 100 |
|---|---|---|---|---|
| 10 | 30 | 29,881 | 104,607 | 187,915 |
| 10 | 60 | 130,454 | 305,434 | 463,927 |
| 10 | 90 | 285,311 | 593,700 | 846,369 |
| 10 | 120 | 485,954 | 957,463 | 1,321,836 |
| 10 | 150 | 727,594 | 1,389,502 | 1,881,912 |
| 10 | 180 | 1,006,991 | 1,884,770 | 2,520,602 |
| 10 | 210 | 1,321,738 | 2,439,451 | 3,233,325 |
| 10 | 240 | 1,669,947 | 3,050,512 | 4,016,413 |
| 10 | 270 | 2,050,081 | 3,715,461 | 4,866,833 |
| 10 | 300 | 2,460,850 | 4,432,197 | 5,782,018 |

**Equation 24(a). Temperature Rise (°F)**

| Mass Exhaust Rate (cfm) | Heat Release Rate (Btu/s) 1000 | 2000 | 4000 | 8000 | 16,000 |
|---|---|---|---|---|---|
| 100 | 29.2 | 58.3 | 116.7 | 233.3 | 466.7 |
| 200 | 14.6 | 29.2 | 58.3 | 116.7 | 233.3 |
| 300 | 9.7 | 19.4 | 38.9 | 77.8 | 155.6 |
| 400 | 7.3 | 14.6 | 29.2 | 58.3 | 116.7 |
| 500 | 5.8 | 11.7 | 23.3 | 46.7 | 93.3 |
| 600 | 4.9 | 9.7 | 19.4 | 38.9 | 77.8 |
| 700 | 4.2 | 8.3 | 16.7 | 33.3 | 66.7 |
| 800 | 3.6 | 7.3 | 14.6 | 29.2 | 58.3 |
| 900 | 3.2 | 6.5 | 13.0 | 25.9 | 51.9 |
| 1000 | 2.9 | 5.8 | 11.7 | 23.3 | 46.7 |

**Equation 27. Opposed Airflow Requirement (fpm)**

| Height of Opening (ft) | Fire Temperature (°F) 200 | 1000 | 1500 | 2000 |
|---|---|---|---|---|
| 5 | 222 | 389 | 416 | 432 |
| 10 | 314 | 550 | 589 | 610 |

## Appendix G Selected References

*This Appendix is not a part of the requirements for this NFPA document, but is included for informational purposes only.*


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