NFPA 92B

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

1995 Edition

National Fire Protection Association, 1 Batterymarch Park, PO Box 9101, Quincy, MA 02269-9101
An International Codes and Standards Organization

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This edition of NFPA 92B, *Guide for Smoke Management Systems in Malls, Atria, and Large Areas*, was prepared by the Technical Committee on Smoke Management Systems and acted on by the National Fire Protection Association, Inc., at its Annual Meeting held May 22-25, 1995, in Denver, CO. It was issued by the Standards Council on July 21, 1995, with an effective date of August 11, 1995, and supersedes all previous editions.

The 1995 edition of this document has been approved by the American National Standards Institute.

Changes other than editorial are indicated by a vertical rule in the margin of the pages on which they appear. These lines are included as an aid to the user in identifying changes from the previous edition.

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 document, NFPA 92B, *Guide for Smoke Management Systems in Malls, Atria, and Large Areas*. The first edition was published in 1991. This 1995 edition is the second.

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

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

Information on referenced publications can be found in Chapter 6 and Appendix 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, noncompartmented spaces. This guide 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, and

(f) Test and maintenance methods.

1-2* Scope. This guide provides methodologies to estimate the location of smoke within a large-volume space from a fire either in the large-volume space or an adjacent space. These methodologies comprise the technical basis to assist in 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. This guide does not provide methodologies to assess the effects of smoke exposure on people, property, or mission continuity.

1-3 Purpose.

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

(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 might be established in other codes and standards or by the authority having jurisdiction.

1-4 Definitions. For the purposes of this guide the following terms have the meanings given in this chapter.

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

Ceiling Jet. A flow of smoke under the ceiling, extending radially from the point of fire plume impingement on the ceiling. Normally, the temperature of the ceiling jet will be greater than the adjacent smoke layer.

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 can open directly into the large-volume space or can 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 on 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 might or might not have a fire resistance rating. Smoke barriers can 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 Safety Leakage Rated Dampers for Use in Smoke-Control Systems*, and is designed to resist the passage of air or smoke. A combination fire and smoke damper is one that meets the requirements of UL 555, *Standard for Safety Fire Dampers*, and UL 555S, *Standard for Safety 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 theoretical boundary between a smoke layer and smoke-free air, as depicted in Figure 1-4. In practice, the smoke layer interface is an effective boundary within a transition buffer zone, which can be several feet thick. Below this effective boundary, the smoke density in the transition zone decreases to zero.

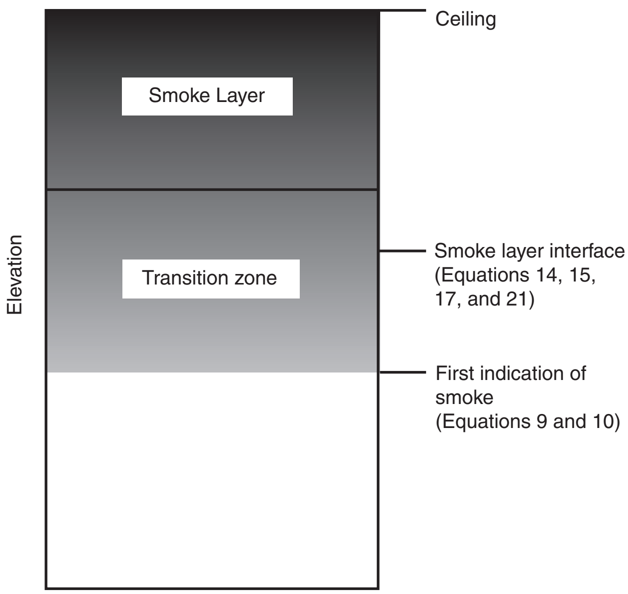

Figure 1-4 Smoke layer interface.

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 on 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 can reduce the heat-release rate and the air entrainment rate into the plume.

1-5.1.2 As a result of the zone model approach, the model assumes uniform properties (smoke concentration and temperature) from the point of interface through the ceiling and horizontally throughout the entire smoke layer.

1-5.1.3 An equilibrium position for the smoke layer interface can be achieved by exhausting the same rate of smoke as is supplied to the smoke layer. Also, smoke exhaust can delay the rate of descent of the smoke layer.

1-5.1.4 Where the smoke layer has descended to the level of adjacent, occupied spaces, prevention of smoke migration from the atrium or mall to the adjacent spaces can be accomplished by physical barriers or opposed airflow. NFPA 92A, *Recommended Practice for Smoke-Control Systems*, provides guidance on the use of walls to restrict smoke migration. Opposed airflow can be used to restrict smoke migration into open adjacent spaces, with air supplied from within the adjacent space. The required volumetric rate of air supplied to achieve the necessary velocity can be substantial.

1-5.1.5 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 airflow 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 might show that no additional venting is required. Alternatively, whether communicating spaces are sprinklered or not, smoke can be prevented from spilling into the large space if the communicating space is exhausted at a rate to cause a sufficient inflow velocity across the interface to the large space.

1-5.3 Detection. Effective design of smoke management systems requires early detection of the smoke condition.

1-5.4 Fire Suppression Systems.

1-5.4.1 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 to cause minimal effect on 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. The likelihood of sprinkler activation is dependent on the heat-release rate of the fire and the ceiling height. Thus, for modest fire sizes, sprinkler operation is most likely to occur in a reasonable time in spaces with lower ceiling heights, such as 8 ft (2.4 m) to 25 ft (7.6 m). This can cause smoke to descend and visibility to be reduced. Equations in Chapter 3 describing smoke filling [(9) and (10)] and production [(14), (15), (17), and (21)] do not apply where a loss of buoyancy due to sprinkler operation has occurred.

1-5.5 Operating Conditions. The smoke management system components should be capable of continuous use at the maximum temperatures expected, using the calculations contained in this guide.

1-5.6 Tenability Analysis. Where the design is based on maintaining tenability of a portion of space, one of two approaches can be pursued. First, the design might depend on preventing the development of a smoke layer in that portion of the space. Second, the design might be based on comparing the qualities of a smoke layer to hazard threshold values. Such a demonstration requires that the effects of smoke on people be evaluated. Such an evaluation is outside the scope of this guide. However, other references are available that present analytical methods for tenability analyses [34].

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, can be addressed in terms of maintaining an adequate air velocity through the openings, with the airflow direction into the zone of fire origin.

1-6.3* Weather Data. The temperature differences between the exterior and interior of the building cause stack effect and determine the stack effect's direction and magnitude. The stack effect must be considered in selection of exhaust fans. The effect of temperature and wind velocity varies with building height, configuration, leakage, and openings in wall and floor construction.

1-6.4 Pressure Differences. The maximum and minimum allowable pressure differences across the boundaries of smoke control zones should be considered (*see NFPA 92A, Recommended Practice for Smoke-Control Systems*). The maximum door opening forces should not exceed the requirements of NFPA *101*®, *Life Safety Code*®, or local codes and regulations. The minimum pressure difference should be such that there will be no significant smoke leakage during building evacuation. The performance of the system is affected by the forces of wind, stack effect, and buoyancy of hot smoke at the time of fire.

1-6.5 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 might 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 might 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 2-1.2.1 and 2-1.2.2:

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 might 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 or barriers as discussed in NFPA 92A, or both.

(b) Fire originates within the communicating space. The management of smoke within this space is discussed in NFPA 92A, *Recommended Practice for Smoke-Control Systems.* 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 needs to 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 from 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 might 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 are 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 can 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 sufficient enough 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 enhances the reliability of the system by providing a timely visual or audible indication of component failure and facilitates prompt repair.

2-3.3 Periodic Testing. Periodic testing is essential to ensure that the system is operational and will reliably perform when needed. Means should be provided for performing periodic tests of the smoke management system 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. Where 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 need to be evaluated. These factors vary widely among atrium designs and need to be considered carefully in selecting detectors for a large-volume space. In addition, the envelope of the large-volume space needs to be evaluated for its contribution to temperature stratification. The height of the large-volume space and its architectural features, such as skylights, will be dominant factors in determining stratification.

2-4.2.1 Environmental factors, such as convection currents and mechanical air movement, also needs to be considered in selecting detector type and location. NFPA 72, *National Fire Alarm Code*, 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 water flow,

(d) Other detectors found to be suitable, and

(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, might be exceptions. 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 NFPA 72, *National Fire Alarm Code*.

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 might 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 water flow 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 multistory ceiling heights and ceiling-mounted sprinklers, sprinkler activation time might be too slow to effectively initiate smoke management. The equations of Chapter 3 should be used to analyze each case. Sprinkler water flow 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 can provide an effective primary initiation means.

2-4.3 Manual Activation. A means of manually starting and stopping the smoke management system should be located to be 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. 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 needs to 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 3-11 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, and

(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 Fire in Communicating Spaces.

2-5.3.1 Communicating spaces can 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, which is there to maintain the design smoke layer interface height.

2-5.3.1.2 The exhaust rate from the large-volume space needs to 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 might or might not present to these spaces should be evaluated.

2-5.3.2 Communicating spaces can 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 can greatly exceed the capacity of the normal building HVAC systems and might 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 evaluated carefully. Exhaust intake and discharge openings should be located so that smoke movement will not interfere with exits. The location of the exhaust discharge to the outside should be located away from outside air intakes to minimize the likelihood of smoke being recirculated.

Chapter 3 Calculation Procedures

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

3-1 Introduction.

3-1.1 Available Approaches. Three different approaches are available. They are:

(a) Scale modeling using a reduced scale physical model following established scaling laws. Small-scale tests are then conducted to determine the requirements and capabilities of the modeled smoke management system.

(b) Algebraic, closed-form equations derived primarily from the correlation of large- and small-scale experimental results.

(c) Compartment fire models using both theory and empirically derived values to estimate conditions in a space.

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

3-1.1.1 Scale Modeling. Scale modeling is especially desirable where the space being evaluated has projections or other unusual arrangements that prevent a free-rising plume. In a scale model, the model is normally proportional in all dimensions to the actual building. The size of the fire and the interpretation of the results are, however, governed by the scaling laws (as given in 3-1.2). While sound, the approach is expensive, time-consuming, and valid only within the range of tests conducted. Since this approach is usually reserved for complex structures, it is important that the test series cover all of the potential variations in factors such as position and size of fire, location and capacity of exhaust and intake flows, variations in internal temperature (stratification or floor-ceiling temperature gradients), and other variables. It is likely that detection will not be appraisable using scale models.

3-1.1.2 Algebraic Equations. Algebraic equations, as contained in this guide, provide a desktop means of calculating individual factors that collectively can be used to establish the design requirements of a smoke management system. The equations presented are considered to be the most accurate, simple, algebraic expressions available for the proposed purposes. In general, they are limited to cases involving fires that burn at a constant rate of heat release ("steady fires" as described in 3-2.2) or fires that increase in rate of heat release as a function of the square of time ("unsteady fires" as described in 3-2.3). The equations are not appropriate for other fire conditions or for a condition that initially grows as a function of time but after reaching a maximum burns at a steady state. In most cases, judicious use of the equations can reasonably overcome this limitation. Each of the equations has been derived from experimental data. In some cases, there is only limited test data and/or the data has been collected within a limited set of fire sizes, space dimensions, or points of measurement. Where possible, comments are included on the range of data used in deriving the equations presented. It is important to consider these limits.

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

3-1.1.3* Compartment Fire Models. Computer capabilities sufficient to execute some of the family of compartment fire models are widely available. All compartment fire models solve the conservation equations for distinct regions (control volumes). Compartment fire models can be generally classed as zone models or field (computational fluid dynamics) models.

3-1.1.3.1 Zone Models. Zone models are the simpler models and can generally be run on personal computers. Zone models usually divide the space into two zones, an upper zone that contains the smoke and hot gases produced by the fire and a lower zone, which is the source of entrainment air. The size of the two zones varies during the course of a fire, depending on the rate of flow from the lower to the upper zone, the rate of exhaust of the upper zone and the temperature of the smoke and gases in the upper zone. Because of the small number of zones, zone models use engineering equations for heat and mass transfer to evaluate the transfer of mass and energy from the lower to the upper zone, the heat and mass losses from the upper zone, and other special features. Generally, the equations assume that conditions are uniform in each respective zone.

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

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

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

3-1.1.3.2 Field Models. Field models [also referred to as computational fluid dynamics (CFD) models] usually require large-capacity computer work stations or mainframe computers and advanced expertise to operate and interpret. Field models, however, can potentially overcome the limitations of zone models and complement or supplant scale models.

As with zone models, field models solve the fundamental conservation equations. In field models, however, the space is divided into many cells (or zones) and use the conservation equations to solve the movement of heat and mass between the zones. Because of the massive number of zones, field models avoid the more generalized engineering equations used in zone models.

Through the use of small cells, field models can examine the situation in much greater detail and account for the impact or irregular shapes and unusual air movements that cannot be addressed by either zone models or algebraic equations. The level of refinement exceeds that which can usually be observed or derived from scale models.

3-1.2 Scale Models.

3-1.2.1* In this guide, the emphasis of scaling activities is placed on modeling hot gas movement through building configurations due to fire. Combustion and flame radiation phenomena are ignored. Fire growth is not modeled. A fire must be specified in terms of a steady or time-varying heat-release rate.

3-1.2.2* Based on the relationships in Table 3-1.2.2, a scale model can be developed. The model should be made large enough to achieve turbulent flow of the full-scale system. Scaling expressions relating full-scale conditions (F) to those in a scale model (m) are presented in Table 3-1.2.2, assuming that the same ambient conditions exist

Table 3-1.2.2 Scaling Expressions

Geometric Position	$x_m = x_F\ (l_m/l_F)$
Temperature	$T_m = T_F$
Pressure Difference	$\Delta p_m = p_F\ (l_m/l_F)$
Velocity	$v_m = v_F\ (l_m/l_F)^{1/2}$
Time	$t_m = t_F\ (l_m/l_F)^{1/2}$
Convective Heat-Release Rate	$Q_{c,m}(t_m) = Q_{c,F}(t_F)\ (l_m/l_F)^{5/2}$
Volumetric Exhaust Rate	$V_{fan,m}(t_m) = V_{fan,F}(t_F)\ (l_m/l_F)^{5/2}$
Thermal Properties of Enclosure	$(k\rho c)_{w,m} = (k\rho c)_{w,F}\ (l_m/l_F)^{0.9}$

where:

c = specific heat of enclosure materials (wall, ceiling)

k = thermal conductivity of enclosure materials (wall, ceiling)

l = length

Δp = pressure difference

Q = heat-release rate

t = time

T = temperature (ambient and smoke)

v = velocity

V = volumetric exhaust rate

x = position

subscripts:

F = full-scale

m = small-scale model

s = smoke

w = wall

3-1.3 The remainder of this chapter presents the algebraic equation-based calculation procedures for the various design parameters, as referred to in the previous sections. The calculation procedures represent an accepted set of algebraic equations and related information available for this edition of the guide.

3-1.4 Establishment of Two-Layer Environment. A delay in activating exhaust fans might allow smoke to descend below the design height of the smoke interface. Initial smoke accumulation at low levels can also be aggravated by initial vertical temperature stratifications that delay transport of smoke to the upper reaches of the 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.

3-1.5 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 needs to 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 can 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 3-2.2.2(a) and determined from Equation (1). Note that if the base fuel package is not circular, an equivalent radius needs to be calculated by equating the floor area covered by the fuel package with that subtended by a circle of the equivalent radius. The entire floor area covered or included between commodities should be considered in the calculations, e.g., if the fuel package consists of the furniture items illustrated in Figure 3-2.2.2(b), 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/sec)

q′′ = incident radiant heat flux required for nonpiloted ignition (Btu/ft^2-sec)

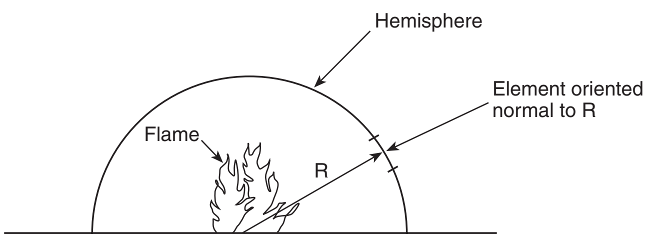

Figure 3-2.2.2(a) Separation distance, R.

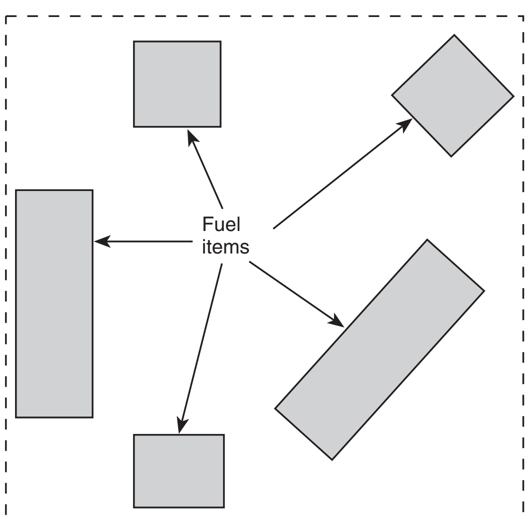

Figure 3-2.2.2(b) Fuel items.

3-2.2.3 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. 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/sec)

t = time after effective ignition (sec)

t_g = growth time (sec)

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

A t-squared profile can be used for engineering purposes until large areas become involved, due to the dynamics of secondary ignitions. Thus, a t-squared 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 are not available for all furniture items nor for "generic" furniture items.

3-2.4.2 If heat-release rate data are 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 might 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 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).

Table 3-3.2.2.1 Excess Gas Temperature at the Time of Automatic Sprinkler Actuation (Steady Fires)

		Gas Temperature Minus Temperature Rating (°F)					
Q_c (Btu/sec)	RTI $(\text{ft-sec})^{1/2}$	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

3-3.2.2* 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 $m^{1/2}/sec^{1/2}$).

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 3-3.2.2.1, based on sprinkler response theory [8], ceiling-level gas temperatures from Equation (3), and a correlation between gas velocity and gas temperature [9]. 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 3-3.2.2.1) 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 3-3.2.2.2, based on sprinkler response theory [8], ceiling-level gas temperatures from Equation (3), and a correlation between gas velocity and gas temperature [9]. 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 3-3.2.2.2) 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 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 within the ceiling jet can be estimated as a function of time based on theoretical generalizations of the limited amount of experimental data. For X ≤100:

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

where:

$$X = tQ^{1/3} / H^{4/3}$$

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

and where:

t = time from ignition (sec)

Q = heat-release rate (steady fire) (Btu/sec)

H = ceiling height above fire surface (ft)

ΔT = temperature rise within ceiling jet (°F)

Equation (3) is based on experimental data from investigations in rooms of varying shapes, characterized by the ratio of the horizontal cross-sectional area of the room to the square of the height of the room (A/H^2). The rooms include those with A/H^2 of 0.9 (in a quiescent room) to 7.0 (in a room with mechanical ventilation at a rate of 1.0 air change per hour and smooth ceilings without obstructions) [10,14]. Use of Equation (3) for $A/H^2 > 7.0$ tends to overestimate the temperature rise at advanced times.

Table 3-3.2.2.2 Excess Gas Temperature at the Time of Automatic Sprinkler Actuation (Unsteady Fires)

t_g (sec)	RTI $(\text{ft-sec})^{1/2}$	Gas Temperature Minus Temperature Rating (°F)				
		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

Subsequent to the original formulation of Equation (3), other data (A/H^2 in the range 2.3 – 8.8) have been found that support the equation [10 (Test 19), 27-31], while some data (A/H^2 ratios of 1.0 and 7.6) indicate considerably higher temperatures than predicted by the equation [32, 33]. The latter were obtained with liquid pools that might have initially burned off vapors evaporated prior to ignition.

Equation (3) incorporates effects of a gradual, although relatively quick initial rise to an approximately steady-state burning rate. Although not rigorously steady, such fire behavior appears representative of what, in practice, might be considered "steady fires."

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

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

(ΔT in °F and t_g in sec, H in ft).

Equation (4) is based on a widely accepted empirical correlation from investigations with extensive, smooth, unobstructed ceilings [9,26], evaluated at r/H = 0.3. Equation (4) was also verified against other experimental data with a limited ceiling [10], where $A/H^2 = 7.4$, $t_g = 480$ sec, and a ventilation rate of 1.0 air change per hour. Equation (4) is most accurate if $A/H^2 \leq 7.4$, $t \leq 480$ sec and the ventilation rate does not exceed 1.0 air change per hour.

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].

$$z_m = 14.7\ Q_c^{1/4}\ (\Delta T/dz)^{-3/8} \tag{5}$$

where:
z_m= maximum height of smoke rise above fire surface (ft)
Q_c = convective portion of the heat-release rate (Btu/sec)
$\Delta T/dz$ = rate of change of ambient temperature with respect to height (°F/ft)

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).

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

where:
$Q_{c,min}$ = minimum convective heat-release rate to overcome stratification (Btu/sec)
H = ceiling height above fire surface (ft)
ΔT_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.

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

Finally, as a third alternative, the maximum ceiling clearance to which a plume of strength, Q_c, can rise for a given ΔT_0 follows from rewriting Equation (7):

$$H_{max} = 74\ Q_c^{2/5}\ \Delta T_0^{3/5} \tag{8}$$

Table 3-5 Equations for Calculating Properties of Smoke Layer

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

Where:
A = horizontal cross-sectional area of space (ft^2)
c_p = specific heat of ambient air (Btu/lb-°F)
D = $L^{-1}\log(I_o/I)$, optical density
L = length of light beam through smoke (ft)
I_o = intensity of light in clear air
I = intensity of light in smoke
D_m DV/m_f, = mass optical density (ft^2/lb) measured in a test stream containing all the smoke from a material test sample
$\dot{m}_f$ = the mass burning rate (lb/sec)
$\dot{V}$ = volumetric flow rate (ft^3/sec)
f_i = yield factor of species i (lb species i/lb fuel)
H = ceiling height (ft)
ΔH_c = heat of complete combustion (Btu/lb)
Q = heat release rate of fire (Btu/sec)
Q_c = convective portion of heat release rate (Btu/sec)
$Q_n = \int(1-\chi_l)\, Q\, dt$
for steady fires: $Q_n = (1-\chi_l)Qt$ (Btu)
for t^2 fires: $Q_n = (1-\chi_l)\, \alpha t^3/3$ (Btu)
$Q_o = \rho_o c_p T_o A (H-z)$ (Btu)
t = time from ignition (sec)
ΔT = temperature rise in smoke layer (°F)
V = volumetric venting rate (cfm)
Y_i = mass fraction of species i (lb species i/lb of smoke)
z = height from top of fuel to smoke layer interface (ft)
α = t^2 fire growth coefficient (Btu/sec^3)
ρ_o = density of ambient air (lb/ft^3)
χ_α = combustion efficiency factor (–), max. value of 1, [21]
χ_l = total heat loss factor from smoke layer to atrium boundaries, max. value of 1, max. temp. rise will occur if $\chi_l = 0$

3-5* Hazardous Conditions. Hazardous conditions can be deemed to occur as a result of unacceptable temperatures, smoke obscuration, or toxic species concentrations (e.g., CO, HCl, HCN) in a smoke layer. Equations to calculate the smoke layer depth, average temperature rise, optical density, and species concentrations during the smoke filling stage and the quasi-steady vented stage are provided in Table 3-5. These equations apply for fire with constant heat-release rates and t-squared fires. They can also be used to calculate the conditions within the smoke layer once the vented conditions exists.

The concepts of this document are based on maintaining the smoke layer interface level by extracting smoke from the smoke layer in a vented scenario. Prior to the exhaust system operation and for a period of time after its initial operation, there is a smoke filling scenario during which the smoke layer interface level used in the venting calculations can be within the smoke layer.

3-6* Height of Smoke Layer Interface at Any Time.

3-6.1 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 3-6.2*),

(b) The mass rate of smoke exhaust equals the mass rate of smoke supplied from the plume to the smoke layer (*see 3-6.3.1*),

(c) The mass rate of smoke exhaust is less than the rate of smoke supplied from the plume to the smoke layer (*see 3-6.3.2*).

3-6.2 Position of Smoke Layer Interface with No Smoke Exhaust Operating.

3-6.2.1 Steady Fires. For steady fires, the height of the initial indications of smoke above the fire surface, z, can be estimated for any time, t, from Equation (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 first indications of smoke above the fire-surface (ft)
H = ceiling height above the fire surface (ft)
t = time (sec)
Q = heat-release rate from steady fire (Btu/sec)
A = cross-sectional area of the space being filled with smoke (ft^2)

Equation (9) is based on experimental data from investigations using uniform cross-sectional areas with respect to height with A/H^2 ratios in the range from 0.9 to 14 and for values of $z/H \geq 0.2$ [7, 10, 12, 13, 14]. This equation is for the worst case condition — a fire away from any walls. The equation provides a conservative estimate of hazard because z relates to the height where there is a first indication of smoke, rather than the smoke layer interface position.

3-6.2.2* Unsteady Fires. The descent of the height of the initial indications of smoke can also be estimated for certain types of unsteady fires, e.g., t-squared fires. From basic theory and limited experimental evidence, the height of the initial indications of the smoke above the fire surface, z, can be estimated for a given time according to the following relation (where calculations yielding z/H > 1.0 mean that the smoke layer has not yet begun to descend).

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

(t and t_g in sec; H in ft; A in ft²; as previously defined)

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

3-6.2.3 The equations presented in 3-6.2.1 and 3-6.2.2 are useful in evaluating the position of the layer at any time after ignition. For a steady fire, the total mass consumption required to sustain the steady heat-release rate over the time period of interest can be determined as:

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

where:
m = total fuel mass consumed (lb)
Q = heat-release rate (Btu/sec)
Δt = duration of fire (sec)
H_c = heat of combustion of fuel (Btu/lb)

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

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

(t_g in sec as previously defined)

3-6.2.4* Varying Cross-Sectional Geometries and Complex Geometries. Equations (9) and (10) are based on experiments conducted in uniform cross-sectional areas. In practice, it is recognized that spaces being evaluated will not always exhibit a simple uniform geometry. The descent of a smoke layer in varying cross sections or complex geometric spaces might be affected by conditions such as sloped ceilings, variations in cross-sectional areas of the space, and projections into the rising plume. Where such irregularities occur, other methods of analysis should be considered. Other methods of analysis, which vary in their complexity but may be useful in dealing with complex and nonuniform geometries, are:

(a) Scale models (*see 3-1.1 and 3-1.2*).

(b) Field models (*see 3-1.1*).

(c) Zone model adaptation — A zone model (*see Section 3-1*) predicated on smoke filling a uniform cross-sectional geometry is modified to recognize the changing cross-sectional areas of a space (*see 3-1.1*). The entrainment source can be modified to account for expected increases or decreases in entrainment due to geometric considerations, such as projections.

(d) Sensitivity analysis — An irregular space is evaluated using Equations (9) and (10) at and between the limits of a maximum height and minimum height identifiable from the geometry of the space using equivalent height or volume considerations.

3-6.3 Position of Smoke Layer Interface with Smoke Exhaust Operating.

3-6.3.1 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 3-7 for the mass rate of smoke supplied to the base of the smoke layer for different plume configurations.

3-6.3.2 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 3-6.2*). Table 3-6.3.2 includes information on the smoke layer position as a function of time for axisymmetric plumes of steady fires given the inequality of the mass rates. For other plume configurations, a computer analysis is required.

3-7 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. The exhaust fan inlets should be sized and distributed in the space to be exhausted to minimize the likelihood of air beneath the smoke layer from being drawn through the layer, sometimes referred to as "plugging." To accomplish this, the velocity of the exhaust inlet should not exceed a value to cause fresh air to be drawn into the smoke layer.

3-7.1 Axisymmetric Plumes. An axisymmetric plume (*see Figure 3-7.1*) 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.

3-7.1.1 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.

3-7.1.2 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 the incorporation of a virtual origin and also compared against other entrainment relations [2,15].

(a) The following entrainment relations are essentially those presented in NFPA 204M, *Guide for Smoke and Heat Venting* [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.

Table 3-6.3.2 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

Where:
z = design height of smoke layer interface above fire source
H = ceiling height above fire source
t = time for smoke layer interface to descend to z
t_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)]

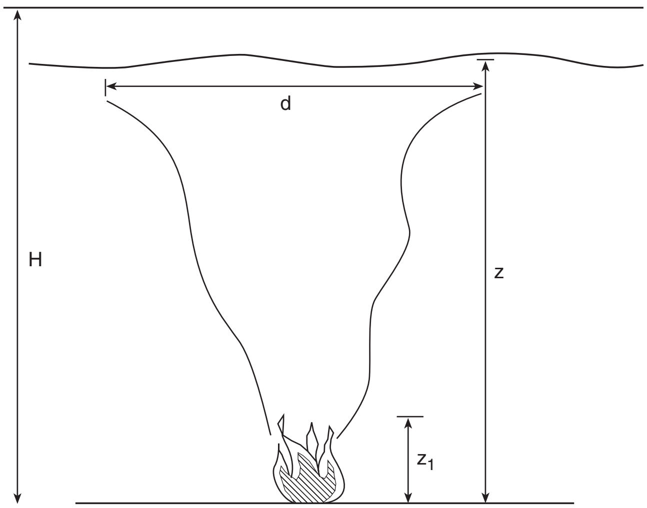

Figure 3-7.1 Axisymmetric plume.

The definition of a limiting elevation, corresponding approximately to the luminous flame height, is given as:

$$z_l = 0.533\ Q_c^{2/5} \tag{13}$$

where:
z_l = limiting elevation (ft)
Q_c = convective portion of heat-release rate (Btu/sec)

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

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

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

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

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

3-7.1.3 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.

3-7.1.4 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.

3-7.1.5* For practical reasons, expressing the smoke production rate in terms of a volumetric rate (cfm) might be preferred over a mass rate. This preference can be accommodated by dividing the mass flow rate by the density of smoke:

$$V = 60\ m/\rho \tag{16}$$

where:
ρ= density of smoke (lb/ft^3)

3-7.1.6 Fires can be located near the edge or a corner of the open space. In this case, entrainment might not be from all sides of the plume, resulting in a lesser smoke production rate than where entrainment can occur from all sides. Thus, conservative design calculations should be conducted assuming that entrainment occurs from all sides.

3-7.2 Balcony Spill Plumes.

3-7.2.1* 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 3-7.2*). Scenarios with balcony spill plumes involve smoke rising above a fire, reaching a ceiling, balcony, or other significant horizontal projection, then traveling horizontally toward the edge of the "balcony." Characteristics of the resulting balcony spill plume depend on characteristics of the fire, width of the spill plume, and height of the ceiling above the fire. In addition, the path of horizontal travel from the plume centerline to the balcony edge is significant.

For situations involving a fire in a communicating space immediately adjacent to the atrium, air entrainment into balcony spill plumes can be calculated from Equation (17):

$$m = 0.12(QW^2)^{1/3} (Z_b + 0.25\ H) \tag{17}$$

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

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

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

Z_b = height above the balcony (ft)

H = height of balcony above fuel (ft)

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

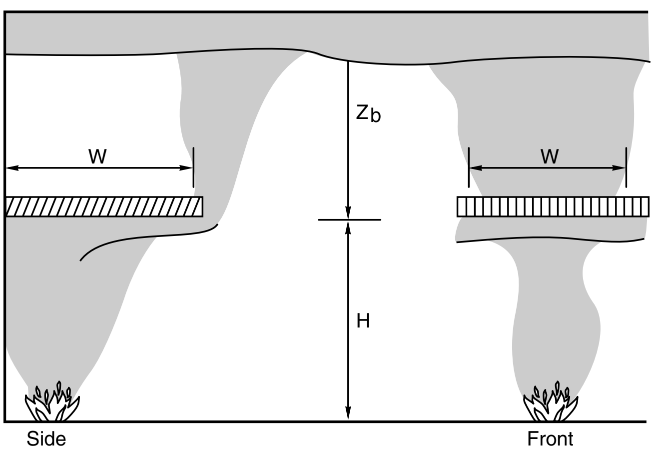

Figure 3-7.2 Balcony spill plume.

3-7.2.2 When z_b is approximately 13 times the width, the balcony spill plume is expected to have the same production rate as an axisymmetric plume. Consequently, for z_b >13W, the smoke production rate from a balcony spill plume should be estimated using Equation (14).

3-7.2.3 The width of the plume, W, can be estimated by considering the presence of any physical barriers protruding below the balcony to restrict horizontal smoke migration under the balcony. In the absence of any barriers, visual observations of the width of the balcony spill plume at the balcony edge were made in a set of small-scale experiments by Morgan and Marshall [17] and analyzed by Law [16]. In these experiments, the fire was in a communicating space, immediately adjacent to the atrium. An equivalent width can be defined by equating the entrainment from an unconfined balcony spill plume to that from a confined balcony spill plume. The equivalent width is evaluated using the following expression:

$$W = w + b$$

where:
W = the width of the plume

w = the width of the opening from the area of origin

b = the distance from the opening to the balcony edge

3-7.3 Window Plumes.

3-7.3.1 Plumes issuing from wall openings, such as doors and windows, into a large-volume, open space are referred to as window plumes (*see Figure 3-7.3*). 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]:

$$Q = 61.2\ A_w H_w^{1/2} \tag{18}$$

where:
Q = heat-release rate (Btu/sec)

A_w = area of ventilation opening (ft^2)

H_w = height of ventilation opening (ft)

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

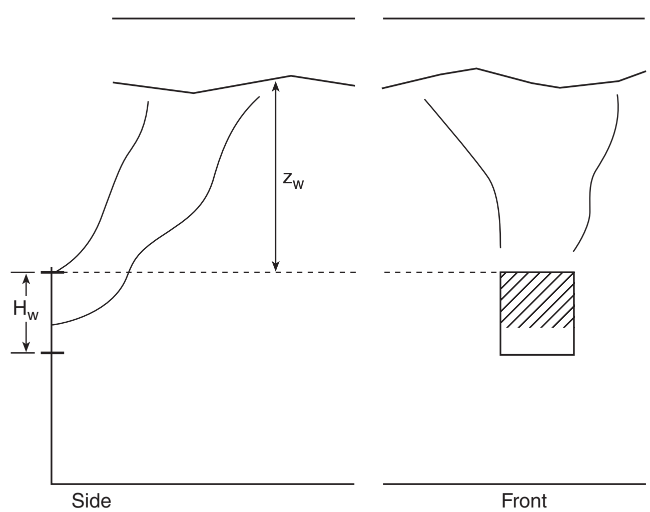

Figure 3-7.3 Window plume.

3-7.3.2 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:

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

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

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

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

Substituting for Q_c from Equation (18),

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

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

3-8 Influence of Plume Contact with Walls. As a plume rises, it also widens. The plume might 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. The overall plume diameter can be estimated as [15]:

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

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 can be estimated as:

$$d = 0.5\ z \tag{23}$$

3-9 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/sec) is recommended, based on flame deflection data [22].

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]:

$$v = 38\ [gH\ (T_f - T_0)/(T_f - 460)]^{1/2} \tag{24}$$

where:

v = air velocity (fpm)

g = acceleration of gravity (32.2 ft/sec^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 (25)]. 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:

$$v_e\ (\text{fpm}) = 17\ [Q/z]^{1/3} \tag{25}$$

where:

v_e = limiting average velocity (fpm)

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

z = distance above the base of the fire to the bottom of the opening (ft). (*See Figure 3-10.2.*)

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 (24) is used to calculate the limiting average velocity (setting $v = v_e$), where $T_f - T_0$ is the value of ΔT from Table 3-5 and $T_f = \Delta T + T_0$.

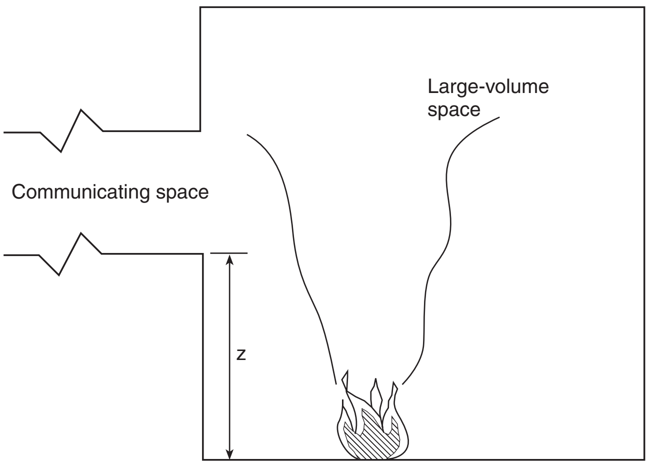

Figure 3-10.2 Measurement of distance above base of fire to bottom of opening.

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 need to be capable of operating in this heated environment.

4-2 Exhaust Fans. Exhaust fans should be selected to operate at the design conditions of the smoke and fire. While dilution with ambient air might significantly cool down the fire temperature, there can 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 impractical, a powered supply system can 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, might not be installed correctly, might not be properly tested, might have a low level of reliability, and might never be maintained.

4-4.2 Coordination. The control system should fully coordinate the smoke management system interlocks and interface with the fire protection signaling system, sprinkler system, HVAC system, and any other related systems.

4-4.3 HVAC System Controls. Operating controls for the HVAC system should accommodate the smoke management mode, which must have the highest priority over all other control modes.

4-4.4 Response Time. The smoke management system activation should be initiated immediately after receipt of an appropriate activation command. The smoke management system should activate individual components such as dampers and fans in sequence as necessary to avoid physical damage to the equipment. (Careful consideration 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 start-up, should allow for full operational mode to be achieved before the conditions in the space exceed the design smoke conditions.

4-4.5 Control System 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 can 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 can 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 fire safety 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 defined clearly prior to component system testing.

5-2.2 Prior to testing, the party responsible for this testing should verify completeness of building construction, including the following architectural features:

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

(b) Firestopping;

(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 72, National Fire Alarm Code*),

(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 might 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 procedures described in 5-3.4.1 through 5-3.4.6.

5-3.4.1 Prior to beginning acceptance testing, all building equipment should be placed in the normal operating mode, including equipment that is not used to implement smoke management, such as toilet exhaust, elevator shaft vents, elevator machine room fans, and similar systems.

5-3.4.2 Wind speed, direction, and outside temperature should be recorded for each test day. If conditions change greatly during the testing, new conditions should be recorded.

5-3.4.3 If standby power has been provided for the operation of the smoke management system, the acceptance testing should be conducted while on both normal and standby power. Disconnect the normal building power at the main service disconnect to simulate true operating conditions in this mode.

5-3.4.4 The acceptance testing should include demonstrating that the correct outputs are produced for a given input for each control sequence specified. Consideration should be given to the following control sequences so that the complete smoke management sequence is demonstrated:

(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 can initiate a single input signal to the smoke management system. Therefore, consideration should be given to establishing the appropriate number of initiating devices and initiating device circuits to be operated to demonstrate the smoke management system operation.

5-3.4.6 Much can be accomplished to demonstrate smoke management system operation without resorting to demonstrations that use smoke or products that simulate smoke.

5-3.5 Large-Volume Space Smoke Management Systems.

5-3.5.1 The large-volume space can come in many configurations, each of which has its own peculiarities. They can 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 can 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 might be dangerous and should not normally be attempted. Any other test is a compromise. If a test of the smoke management system for building acceptance is mandated by the authority having jurisdiction, such a test condition would become the basis of design and might not in any way simulate any real fire condition. More importantly, it could be a deception and provide a false sense of security that the smoke management system would perform adequately in a real fire emergency.

Smoke bomb tests do NOT provide the heat, buoyancy, and entrainment of a real fire and are NOT useful 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 might assume beneficial use of the smoke management system wherever 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 wherever there are system changes and modifications. Documentation should be updated to reflect these changes or modifications.

5-4 Periodic Testing.

5-4.1 During the life of the building, maintenance is essential to ensure that the smoke management system will perform its intended function under fire conditions. Proper maintenance of the system should, as a minimum, include the periodic testing of all equipment such as initiating devices, fans, dampers, controls, doors, and windows. The equipment should be maintained in accordance with the manufacturer's recommendations. See NFPA 90A, *Standard for the Installation of Air Conditioning and Ventilating Systems*, for suggested maintenance practices.

5-4.2 The periodic tests should determine that the installed systems 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 might have to be made for the introduction of large quantities of outside air into occupied areas or computer centers when outside temperature and humidity conditions are extreme, and such unconditioned air might damage contents. Since smoke management systems can override limit controls such as freezestats, tests should be conducted when outside air conditions will not cause damage to equipment and systems.

Chapter 6 Referenced Publications

6-1 The following documents or portions thereof are referenced within this guide and should be considered 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*, 1996 edition.
NFPA 72, *National Fire Alarm Code*, 1993 edition.
NFPA 90A, *Standard for the Installation of Air Conditioning and Ventilating Systems*, 1993 edition.
NFPA 92A, *Recommended Practice for Smoke-Control Systems*, 1993 edition.
NFPA *101*, *Life Safety Code*, 1994 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 Safety Fire Dampers.*
UL 555S-1993, *Standard for Safety Leakage Rated Dampers for Use in Smoke-Control Systems.*

Appendix A Explanatory Material

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

A-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 might 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-3-1.1.3 Common simplifications of zone models are listed in Table A-3-1.1.3(a).

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

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

The items the modeler must accurately characterize are the fuel, the compartment, and the ambient conditions, as indicated in Table A-3-1.1.3(b). The fuel heat-release rate is an important feature to describe. There are many other details of the fuel that also effect fire growth, such as species production, radiative heat loss fraction, fuel-to-air combustion ratio, and heat of combustion. However, the desired accuracy of the answer dictates which of these should be included and which can be ignored. Compartment vent descriptions must also be properly evaluated. Often, leakage areas can account for substantial, unanticipated gas flows, especially in instances of extreme weather conditions with regard to temperature or wind.

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

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

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

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

Table A-3-1.1.3(a) Simplifications in Zone Models

Fuel

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

Plumes

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

Layers

- Hot stagnation layers at the ceiling are not simulated
- Uniform in temperature

Heat Transfer

- Some models do not distinguish between thermally-thin and thermally-thick walls
- No heat transfer via barriers from room to room
- Momentum effects neglected

Ventilation

- Mixing at vents is correlationally determined

Table A-3-1.1.3(b) Simplifications in Field Models

Burning Fuel Description

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

Compartment Description

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

Ambient Conditions Description

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

A-3-1.2.1 A more complete review of scaling techniques and examples can be found in the literature [35]. Smoke flow studies have been made by Heskestad [36] and Quintiere, McCaffrey, and Kashiwagi [37]. Analog techniques using a water and saltwater system are also available [38]. Smoke flow modeling for buildings is based on maintaining a balance between the buoyancy and convective "forces" while ignoring viscous and heat conduction effects. Neglecting these terms is not valid near solid boundaries. Some compensation can be made in the scale model by selecting different materials of construction.

A-3-1.2.2 Dimensionless groups can be formulated for a situation involving a heat source representing a fire along with exhaust and make-up air supply fans of a given volumetric flow rate. The solution of the gas temperature (T), velocity (v), pressure (p), surface temperature (T_s) expressed in dimensionless terms and as a function of x, y, z, and time (t) are:

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

where:

l = a characteristic length

g = gravitational acceleration

T_o = ambient temperature

ρ_o = ambient density

Π_1, Π_2, and Π_3 are dimensionless groups arising from the energy release of the fire, fan flows, and wall heat transfer

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

where:

Q = the energy release rate of the fire

c_p = the specific heat of the ambient air

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

where:

V_{fan} = the volumetric flow rate of the exhaust fan

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

where:

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

μ = the gas viscosity

k = the gas thermal conductivity

The expression of Π_3 is applicable to a thermally-thick construction material. Additional dimensionless terms (Πs) are needed if wall thickness and radiation effects are significant. Π_3 attempts to correct for heat loss at the boundary by permitting a different construction material in the scale model in order to maintain a balance for the heat losses.

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

The scaling expression for the fire heat-release rate follows from preserving Π_1. Similarly, expressions for the volumetric exhaust rate and wall thermal properties are obtained from preserving Π_2 and Π_3. The wall properties condition is easily met by selecting a construction material that is noncombustible and closely matches $(k\rho c)_w$ with a material of sufficient thickness to maintain the thermally-thick condition.

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-3-3.2.2 Tables 3-3.2.2.1 and 3-3.2.2.2 list excess gas temperatures at the time of sprinkler actuation for steady and unsteady (t-squared) fires [47]. The tables assume a sprinkler temperature rating of near 165°F (74°C) and a conduction parameter (C) of 1.8 ft$^{1/2}$/sec$^{1/2}$ (1 m$^{1/2}$/sec$^{1/2}$).

The tables are based on the following response equation for heat-responsive elements of sprinklers [8]:

$$\frac{d(\Delta T_e)}{dt} = \frac{u^{1/2}}{RTI}\left[\Delta T - (1 + C/u^{1/2})\,\Delta T_e\right] \tag{A-1}$$

where:

ΔT_e = temperature rise (from ambient) of heat-responsive element

t = time

u = gas velocity at sprinkler site

ΔT_g = gas temperature rise (from ambient) at sprinkler site

RTI = response time index of sprinkler (tau$^{1/2}$, where τ is the sprinkler time constant)

C = conduction parameter of sprinkler, representing heat loss by conduction to the sprinkler mount from the heat-responsive element.

Gas temperatures for steady fires were taken from Equation (3), and gas temperatures for t-squared fires were taken from Equation (4). Gas velocities were evaluated from a relation between gas velocity and gas temperature rise [9] (valid for r/H ≥ 0.3):

$$u/[(\Delta T_g / T_\infty)\, gH]^{1/2} = 0.59\ (r/H)^{-0.63} \tag{A-2}$$

where:

T_∞ = ambient air temperature

g = acceleration of gravity

H = ceiling height (above combustibles)

r = radius from fire axis

Since the sprinkler response information in Tables 3-3.2.2.1 and 3-3.2.2.2 relates to representative behavior in the r/H range 0 – 0.6, Equation (2) was evaluated for r/H = 0.3 and normal ambient conditions:

$$u = 0.23\,[\Delta T_g\ H]^{1/2} \qquad \text{(A-3)}$$

where:
u is in m/s
ΔT_g in °C
H in m.

The various cases in Tables 3-3.2.2.1 and 3-3.2.2.2 were solved by approximating the time-temperature curves using linear segments. For a time segment of linear rate of rise in gas temperature, ΔT_g /dt = b, the solution to Equation (A-1) is:

$$\Delta T_e = \frac{\beta}{\left(1 + Cu^{-1/2}\right)}\left[t - \frac{RTI\,u^{-1/2}}{\left(1 + Cu^{-1/2}\right)}\left(1 - \exp\left(-t/RTI\,u^{-1/2}/\left(1 - Cu^{-1/2}\right)\right)\right)\right] \qquad \text{(A-4)}$$

where:
ΔT_e and t are measured from the beginning of the segment. The velocity, u, was evaluated from Equation (A-3) at a representative value for ΔT_g in the segment. The total rise in element temperature during a segment was the rise at the end of the preceding segment, plus the rise calculated in the current segment, using Equation (A-4). The calculations continued until the element temperature rise reached the actuation value (74°C – 20°C = 54°C), at which time the excess of the gas temperature above the actuation value of the heat responsive element was calculated, to be entered in Tables 3-3.2.2.1 and 3-3.2.2.2.

For the steady fires (Table 3-3.2.2.1), detailed calculations were made according to this procedure, using values of $u^{1/2}$ in Equation (A-4) equal to the average of the values at the beginning and the end of each segment.

For the unsteady fires (Table 3-3.2.2.2), a somewhat simplified approach was employed because of the magnitude of the task, taking advantage of the fact that the rate of rise in gas temperature changes only slowly with time, being proportional to $t^{1/3}$. A constant rate of rise was assumed, adopting the value existing at the moment the gas temperature was equal to the sprinkler temperature rating. Furthermore, the gas velocity was assumed constant at the value corresponding to this gas temperature, using Equation (A-3). Hence, the calculations were approximate, but they were considered adequate in view of other uncertainties. The values in the upper left-hand corner in Table 3-3.2.2.2 (for t_g = 50 sec; RTI = 54,180,630; H = 13 ft) are quite high, for which one might question the applicability of the approximate method. These cases were recalculated, employing a number of linear segments in each case; the results were within 1°C of those listed by the approximate method.

A-3-5 For design purposes, the topic of algebraic equations for gas concentrations and obscuration of visibility can be addressed for two limit cases:

(a) The smoke filling scenario, where all products of combustion are assumed to accumulate in the descending smoke layer.

(b) The quasi-steady vented scenario, where a quasi-steady balance exists between the rates of inflow into and outflow from the smoke layer.

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

Methods to analyze the gas composition and optical characteristics for the two limit cases can be addressed in terms of a number of algebraic equations. These algebraic equations are exact, but the data used in these equations are uncertain [56]. The user should be made aware of these uncertainties to the extent they are known.

Smoke Filling Stage — Optical Properties Analysis

The average optical density of the descending smoke layer can be estimated if the mass optical density of the fuel can be reasonably estimated. Equation (A-5) is used to estimate the optical density as a function of the mass optical density, the mass of fuel consumed, and the volume of the smoke layer.

$$D = \frac{D_m m_f}{V_u} = \frac{D_m \int_0^t \dot{m}_f dt}{A z_u(t)} \qquad \text{(A-5)}$$

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

For the case of a flat ceiling, negligible plume area and a fire with constant mass and heat-release rates, Equation (A-5) evaluates as:

$$D = \frac{D_m Qt}{\chi_a \Delta H_c A_u H}\left\{1 - \left[1 + \frac{2t}{3\tau}\right]^{-3/2}\right\}^{-1} \qquad \text{(A-6)}$$

$$\tau = \frac{V}{V_{ent}} = \frac{AH}{k_v Q^{1/3} H^{5/3}} = \frac{AH}{k_v(\alpha_n t^n)^{1/3} H^{5/3}} \qquad \text{(A-6.1)}$$

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

For the case of a flat ceiling, negligible plume area and a t-squared fire, Equation (A-5) evaluates as:

$$D = \frac{D_m \alpha t^3}{3\chi_a \Delta H_c AH}\left\{1 - \left[1 + \frac{2k_v \alpha^{1/3} t^{5/3} H^{2/3}}{5A}\right]^{-3/2}\right\}^{-1} \quad \text{(A-7)}$$

where:

α = fire growth rate = $1000/(t_g)^2$ (sec)

For other scenarios, appropriate values must be substituted into Equation (A-5). For some scenarios, numerical integration might be necessary.

Smoke Filling Stage — Layer Composition Analysis

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

$$\dot{m}_i = f_i \dot{m}_f \quad \text{(A-8)}$$

where:

f_i = yield factor $(lb_{product}/lb_{fuel})$ $(kg_{product}/kg_{fuel})$

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

$$Y_i = \frac{m_i}{\sum_i m_i} \quad \text{(A-9)}$$

where:

Y_i = mass fraction $(lb_{species}/lb_{total})$ $(kg_{species}/kg_{total})$

The term in the numerator of Equation (A-9) is calculated, similar to Equation (A-5), as:

$$m_i = \int_0^t \dot{m}_i dt = \int_0^t f_i \dot{m} dt = \int_0^t f_i \frac{Q}{\chi_a \Delta H_c} dt \quad \text{(A-10)}$$

For the case of a constant yield factor and a t-squared fire growth rate, Equation (A-10) evaluates as:

$$\dot{m}_i = f_i \int_0^t \frac{\alpha t^2}{\chi_a \Delta H_c} dt = \frac{f_i \alpha t^3}{3\chi_a \Delta H_c} \quad \text{(A-11)}$$

For the case of a constant yield factor and a steady fire, Equation (A-10) evaluates as:

$$m_i = \int_0^t f_i \frac{Q}{\chi_a \Delta H_c} dt = \frac{f_i Q t}{\chi_a \Delta H_c} \quad \text{(A-12)}$$

The term in the denominator of Equation (A-9) represents the total mass of the smoke layer. Typically, the mass of fuel released is negligible compared to the mass of air entrained into the smoke layer, so the total mass of the smoke layer can be approximated as:

$$\sum_i m_i = \bar{\rho}\; V_u \frac{\rho_o T_o V_u}{\bar{T}} \quad \text{(A-13)}$$

For the case where the temperature rise of the smoke layer is small relative to the ambient absolute temperature (i.e., $\bar{T}/T_o \approx 1$), Equation (A-13) reduces to:

$$\sum_i m_i = p_o V_u \quad \text{(A-14)}$$

Substituting Equations (A-11) and (A-14) into Equation (A-9) yields, for the t-squared fire:

$$Y_i = \frac{f_i \alpha t^3}{3\rho_o V_u \chi_a \Delta H_c} \quad \text{(A-15)}$$

Substituting Equations (A-12) and (A-14) into Equation (A-9) yields, for the steady fire:

$$Y_i = \frac{f_i Q t}{\rho_o V_u \chi_a \Delta H_c} \quad \text{(A-16)}$$

For a fire that grows as a t-squared fire from Q = O at time t = 0 to $Q = Q_{qs}$ at time $t = t_{qs}$, then continues to burn indefinitely at $Q = Q_{qs}$. Equations (A-15) and (A-16) can be combined to yield:

$$Y_i = \frac{f_i[\alpha t_{qs}^3/3 + Q_{qs}(t - t_{qs})]}{\rho_o V_u \chi_a \Delta H_c} \quad \text{(A-17)}$$

The volume of the smoke layer, V_u, in these equations is evaluated by the methods presented in Section 3-7 with $V_u = A\,(H - z)$.

Quasi-Steady Ventilated Stage — Optical Properties Analysis

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

$$D = \frac{D_m \dot{m}_f}{V} = \frac{D_m Q}{\chi_a \Delta H_c V} \quad \text{(A-18)}$$

Equation (A-18) can be used to determine the average optical density of the smoke layer for a given exhaust rate. Alternatively, the required exhaust rate needed to produce a particular optical density, D, can be determined by rearranging Equation (A-18) as:

$$V = \frac{D_m Q}{D \chi_a \Delta H_c} \quad \text{(A-19)}$$

Use of Equations (A-18) and (A-19) requires knowledge of the mass optical density, D_m, of the smoke. Mass optical densities for a variety of fuels are reported by Tewarson (1988) [21] and by Mulholland (1988) [61].

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

Quasi-Steady Ventilated Stage — Layer Composition Analysis

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

$$Y_i = \frac{\dot{m}_i}{\sum_i \dot{m}_i} \quad \text{(A-20)}$$

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

$$\dot{m}_i = f_i \dot{m}_f = f_i \frac{Q}{\chi_a \Delta H_c} \quad \text{(A-21)}$$

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

$$\sum_i \dot{m}_i = \bar{\rho} \; V = \rho_o V_{ent} = \rho_o (V - V_{exp}) \quad \text{(A-22)}$$

Substituting Equations (A-21) and (A-22) into Equation (A-20) permits calculation of the mass fraction for each species i of interest in terms of a known exhaust rate:

$$Y_i - Y_{i,o} = \frac{f_i Q}{\rho_o \chi_a \Delta H_c (V - V_{exp})} \quad \text{(A-23)}$$

To determine the required volumetric exhaust rate needed to limit the mass fraction of some species i to a limit value, Y_i, Equation (A-23) is rearranged to:

$$V = V_{exp} + \frac{f_i Q}{\rho_o \chi_a \Delta H_c (Y_i - Y_{i,o})} \quad \text{(A-24)}$$

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

$$V_{exp} = \frac{Q_n}{\rho_o c_p T_o} = \frac{(1 - \chi_i) Q}{\rho_o c_p T_o} \quad \text{(A-25)}$$

A-3-6 Limiting the size and distribution of the exhaust fan inlets is intended to prevent the smoke from cooling before it can be exhausted by keeping the layer up near the ceiling. This is particularly important for spaces where the length is greater than the height, such as shopping malls.

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

A-3-6.2.2 Equations (9) and (10) are empirically-based equations for estimating the smoke layer interface position during the smoke filling process. This review of Equations (9) and (10) is divided into two parts:

(a) Comparison of the results of both Equations (9) and (10) with those from theoretically based equations (with empirically determined constants, hereafter referred to as ASET-based equations.

(b) Evaluate the predictive capability of Equation (9) and an ASET-based equation by comparing the output from the equations with experimental data.

Comparisons with ASET-based Equations

Comparisons of the NFPA 92B equations for smoke filling with ASET-based equations provide an indication of the differences between empirically based equations, e.g., Equations (9) and (10), with those that are based principally on theory.

Steady Fires

A theoretically-based equation for smoke filling can be derived using the laws of conservation of mass and energy to determine the additional volume being supplied to the upper layer [56]. Using Zukoski's plume entrainment correlation [57]:

$$z/H = \left[1 + \frac{2k_v (tQ^{1/3}/H^{4/3})}{2(A/H^2)}\right]^{-3/2} \quad \text{(A-26)}$$

where:

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

A comparison of z/H predicted by Equations (9) and (A-26) is presented in Figure A-3-6.2.2(a) for a ceiling height of 30 m, a steady fire size of 5 MW, and a wide range of A/H^2 ratios. In general, the agreement between the two equations is reasonable. Equation (9) predicts a lower smoke layer interface position at most times, except in the case of the voluminous space represented by A/H^2 of 10. In this case, Equation (9) indicates a delay of approximately 100 sec before a layer forms, while Equation (A-26) indicates immediate formation of the layer. Such a delay is reasonable for such a large space. This delay can could be addressed by including an additional term in Equation (A-26) to account for the transport lag [48]. The transport lag is estimated as 37 sec for this case with a height of 30 m and cross-sectional area of 9,000 m^2.

While the comparison in Figure A-3-6.2.2(a) is useful, it only applies to selected values of A, H, and Q. This comparison can be generalized for all values of A, H, and Q by forming a ratio of the two equations expressed in terms of t.

$$\frac{t_{eqnA-1}}{t_{eqn9}} = \frac{3}{2k_v} \frac{\left[\left(\frac{Z}{H}\right)^{-2/3} - 1\right]}{\exp\left(\frac{1.11 - \frac{Z}{H}}{0.28}\right)} \quad \text{(A-27)}$$

Figure A-3-6.2.2(b) indicates the relationship of the time ratio with the normalized smoke layer depth, (H – z)/H. For perfect agreement between the two equations, the time ratio should have a value of 1.0. However, the time ratio varies appreciably. The time ratio is within 20 percent of 1.0 only for a very small range. For normalized smoke layer depths less than 0.13 (or a normalized clear height of 0.87), Equation (A-26) always predicts a shorter time to reach a particular depth than Equation (9). Conversely, Equation (9) predicts shorter times to attain any normalized smoke layer depth in excess of 0.13.

The time ratio is relatively insensitive for values of (H – z)/H, ranging from 0.4 to 0.6. Within this range, the time ratio is nominally 1.5, i.e., the time predicted by Equation (A-26) to obtain a smoke layer of a particular depth is 50 percent greater than that predicted by Equation (9). Alternatively, Equation (9) predicts a more rapid descent to this range of smoke layer depths than Equation (A-26).

T-squared Fires

A similar comparison of the empirically-based Equation (10) and a theoretically-based equation for t-squared fires can be conducted. The ASET-based equation is:

$$z/H = \left[1 + \frac{20 K_v t^{5/3} / H^{-4/2}}{t_g^{\ 2/3} A/H^2} \right]^{-3/2} \qquad \text{(A-28)}$$

where:

t_g = fire growth rate (sec)

A comparison of the predicted z/H values are presented in Figure A-3-6.2.2(c) for a ceiling height of 30 m, a moderate fire growth rate (t_g = 300 sec), and a wide range of A/H^2 ratios. For values of A/H^2 up to 1.0, the agreement appears very reasonable once the smoke layer has formed. Again, the empirically derived equation implicitly includes the transport lag. For A/H^2 of 10.0, the delay for a smoke layer to form is greater than that for smaller A/H^2 ratios such that reasonable agreement in smoke layer interface position is not achieved until approximately 800 sec. The estimated transport lag is 206 sec [48].

The value of z/H of 0.59 for the point of intersection of the various curves for the two equations is a constant, independent of the values for A, H, and Q. Thus, for values of z/H > 0.59, Equation (A-28) estimates a shorter time to attain a particular position of the smoke layer interface, where Equation (10) estimates a faster time for lesser values of z/H.

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

$$\frac{t_{eqnA-2}}{t_{eqn10}} = \frac{(.91)^{-.69}}{4k_v^{-.6}} \quad \frac{\left[\left(\frac{Z}{H}\right)^{-2/3} - 1\right]^{.6}}{\left(\frac{Z}{H}\right)^{-.69}} \qquad \text{(A-29)}$$

The relationship of the time ratio for various normalized smoke layer depths, (H – z)/H, is provided in Figure A-3-6.2.2(d). In general, the agreement between the two predicted times for t-squared fires is much better than that for steady fires, with the predicted time using Equation (A-28) being within 20 percent of that from Equation (10) for (H – z)/H values from 0.26 to 0.80. As in the case of the steady fire, the time ratio is less than 1.0 for small normalized smoke layer depths. However, in this case, the time ratio does not exceed 1.0 until the normalized smoke layer depth is at least 0.40.

Large-scale Experimental Programs in Tall Ceiling Spaces

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

The predictive capability of Equation (A-26) is examined by comparing the output to large scale experimental data. Sources of the experimental data involving a range of ceiling heights from 2.4 m to 12.5 m as well as room sizes and fire scenarios are identified in Table A-3-6.2.2. Included in the table are the data sources referenced in the initial development of Equation (9) of NFPA 92B [49]. Two additional sets of experimental data have become available since the committee's initial analysis [50,51]. Comprehensive descriptions of the test programs are provided elsewhere [53-56]. Because the two additional sets of data were collected from fires in spaces with significantly greater ceiling heights than in the initial sets of data, the new sets of data are of particular interest.

The measured and predicted smoke layer positions as a function of time from the previous and two new sets of data are presented in Figure A-3-6.2.2(e). The data identified as "The Committee's" includes all of the data upon which the committee based initial development of Equation (9). The new sets of data are identified separately. As indicated in the figure, the smoke layer position from the data analyzed is between that measured by NRCC and BRI. Thus, despite the differences in ceiling height, the new and initial sets of data appear to be reasonably similar. The graph labeled "NFPA 92B " depicts the predictions of Equation (9). In general, agreement between the predictions from both Equations (9) and (A-26) and the experimental data is very reasonable. Equation (9) provides a lower limit of the experimental data, including the new NRCC data. Equation (A-26) appears to predict a mid-range value of the data.

Equations comparable to Equations (9) and (A-26) can be derived for variable cross-sectional areas and for fires that follow a power law, e.g., t-squared fires. In addition, algebraic equations pertaining to a variety of smoke layer characteristics are available, including temperature, light obscuration, and species concentration [56]. These equations are applicable to evaluating transient conditions prior to operation of the smoke management system or equilibrium conditionsd with an operational smoke management system. Thus, a variety of algebraic equations are available and can serve as useful tools for relatively elementary designs or as checks of specific aspects of computer calculations for more complicated situations.

A-3-6.2.4 In the absence of an analysis using scale models, field models, or zone model adaptation, a sensitivity analysis should be considered. A sensitivity analysis can provide important information to assist in engineering judgments regarding the use of Equations (9) and (10) for complex and nonuniform geometries. An example of a sensitivity analysis is illustrated as follows for a large space having a nonflat ceiling geometry.

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

In the case of the geometry shown in Figure A-3-6.2.4(a), this would be done as follows:

(a) Convert the actual nonrectangular vertical cross-section area to a rectangular vertical cross section of equal area.

(b) The height dimension corresponding to the equivalent rectangular cross section would then be used as a substitute height factor H_{sub} in Equation (10).

Results of Equation (10) should be compared with other minimum and maximum conditions as indicated by Figure A-3-6.2.4(b).

Table A-3-6.2.2 Summary of Full Scale Experiments

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

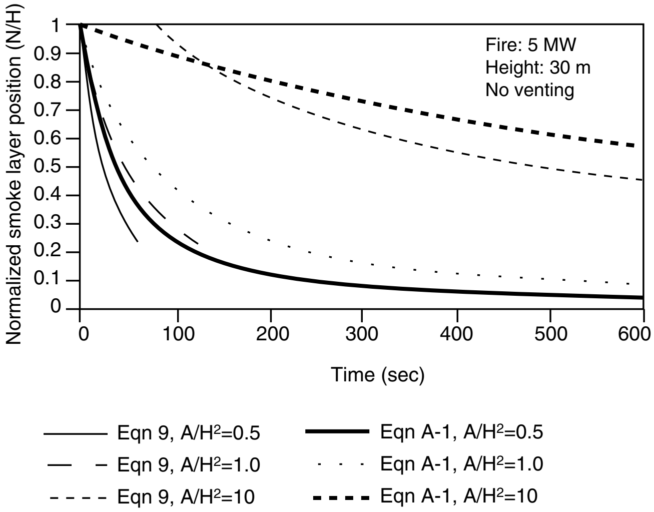

Figure A-3-6.2.2(a) Comparison of algebraic equations, Equations (9) and (A-1): steady fire.

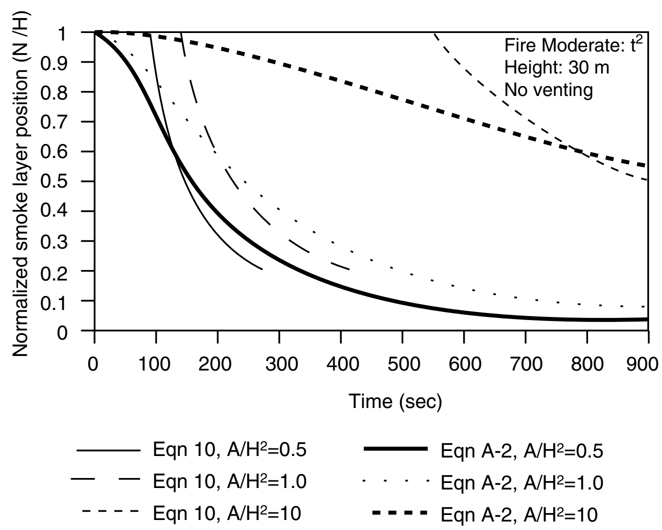

Figure A-3-6.2.2(c) Comparison of algebraic equations, Equations (10) and (A-2): t-squared fire.

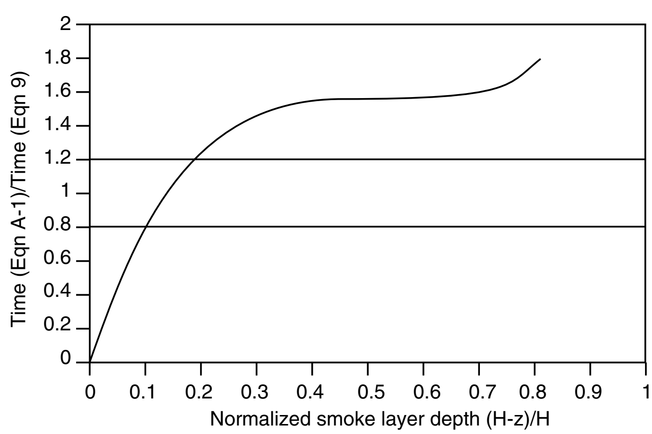

Figure A-3-6.2.2(b) Comparison of algebraic equations, Equations (9) and (A-1): steady fire.

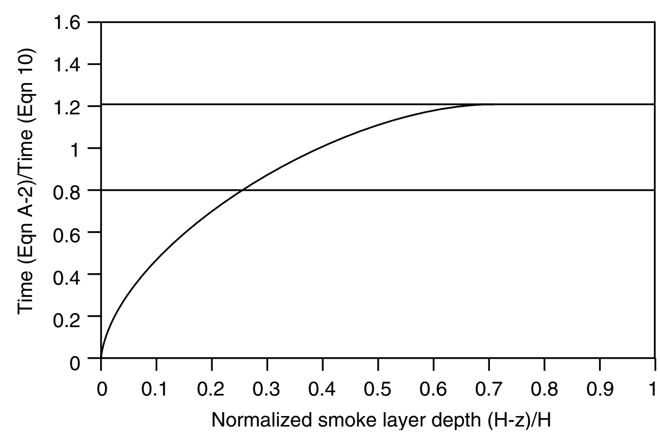

Figure A-3-6.2.2(d) Comparison of algebraic equations, Equations (10) and (A-2): t-squared fire.

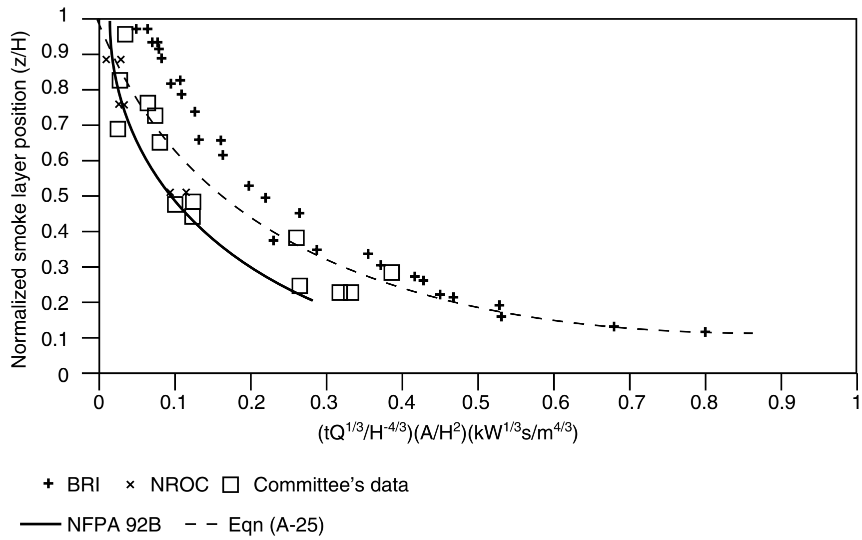

Figure A-3-6.2.2(e) Comparison of smoke layer position, experimental data vs. predictions.

An appropriate method of comparison could be a graph of Equation (10) as shown in Figure A-3-6.2.4(c). Assume that the building in question can be evacuated in three minutes and that the design criteria requires the smoke layer to remain available 10 ft above the floor at this time. A review of the curves would indicate that the smoke layer heights as calculated for the substitute case is appropriate. This conclusion can be drawn by noting that neither the extreme minimum height case (H = 30 ft, W = 60 ft) or the maximum height case (H = 60 ft) offer an expected answer, but the results for two cases (H = 41.6, W = 60; and H = 30, W = 83.3) can be judged to reasonably approximate the behavior of the nonuniform space. It might otherwise be unreasonable to expect the behavior indicated by the maximum or minimum cases.

A-3-7.1.5 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:

$$\rho/\rho_o = 528/(460 + T)$$

where:

ρ_0 = 0.075 (lb/ft^3)

ρ = density of smoke at temperature (lb/ft^3)

T = temperature of smoke (°F)

A-3-7.2.1 Agreement of the predictions from Equation (17) with those from small-scale experimental efforts is presented in Figure A-3-7.2.1. Whereas the agreement is quite good, the results are only from two small-scale experimental programs.

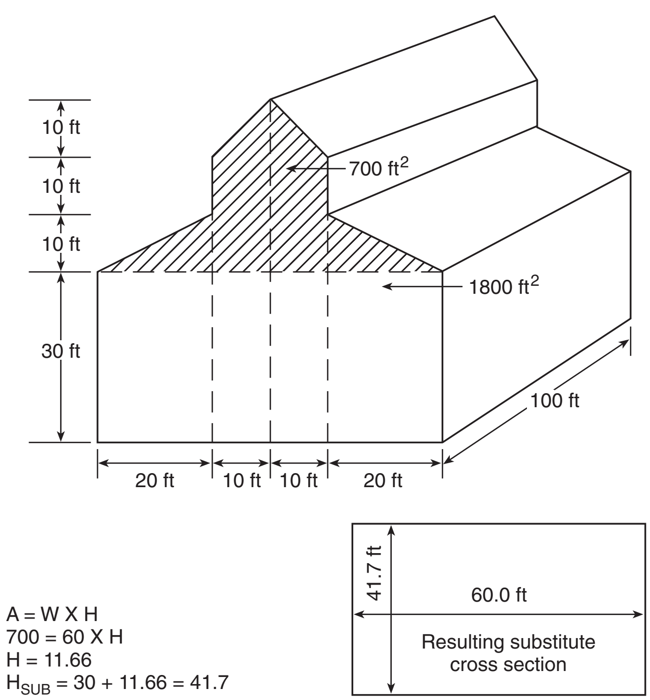

Figure A-3-6.2.4(a) Large space with nonflat ceiling geometry.

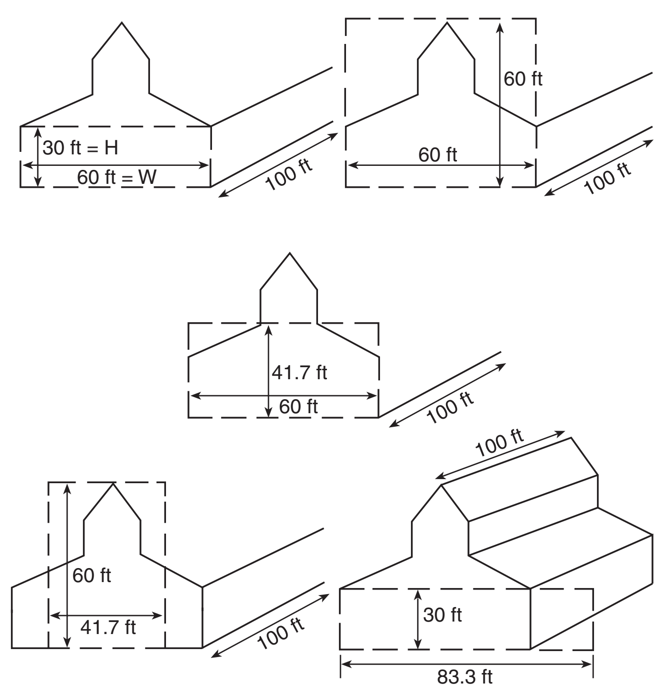

Figure A-3-6.2.4(b) Other nonuniform geometry considerations.

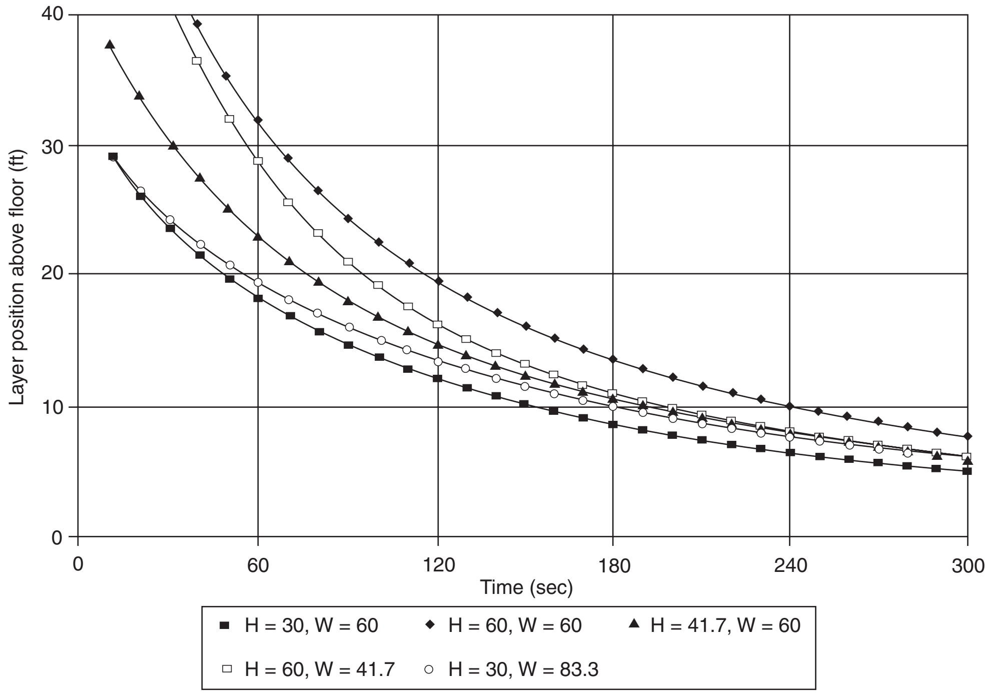

Figure A-3-6.2.4(c) Comparison data for guidance on nonrectangular geometries-growing fire.

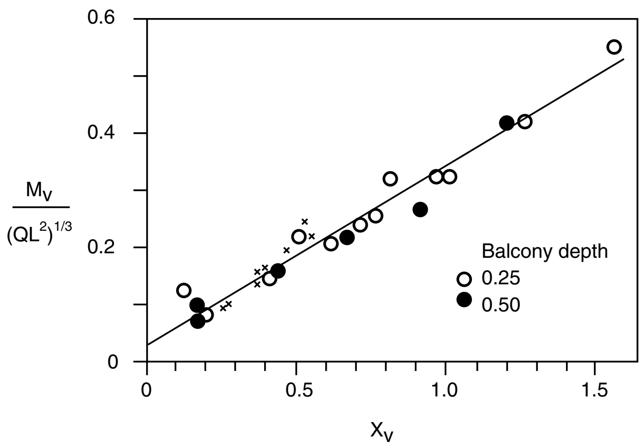

Figure A-3-7.2.1 Agreement between predictions and experimental values. [17,61]

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 informational 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 might 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. Tables B-1 andB-2 give heat-release data for fuels burning in the open [24].

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

Commodity	Heat Release Rate (Btu/sec)
Flammable liquid pool	290/ft^2 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/ft^2 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/ft^2 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/ft^2 of surface

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

Table 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 percent combustion efficiency.

Commodity	Btu/sec per ft^2 of Floor Area
Wood pallets, stacked 1 $^1/_2$ ft high (6-12% moisture)	125
Wood pallets, stacked 5 ft high (6-12% moisture)	350
Wood pallets, stacked 10 ft high (6-12% moisture)	600
Wood pallets, stacked 16 ft high (6-12% moisture)	900
Mail bags, filled, stored 5 ft high	35
Cartons, compartmented, stacked 15 ft high	150
PE letter trays, filled, stacked 5 ft high on cart	750
PE trash barrels in cartons, stacked 15 ft high	175
PE fiberglass shower stalls in cartons, stacked 15 ft high	125
PE bottles packed in Item 6	550
PE bottles in cartons, stacked 15 ft high	175
PU insulation board, rigid foam, stacked 15 ft high	170
PS jars packed in Item 6	1,250
PS tubs nested in cartons, stacked 14 ft high	475
PS toy parts in cartons, stacked 15 ft high	180
PS insulation board, rigid foam, stacked 14 ft high	290
PVC bottles packed in Item 6	300
PP tubs packed in Item 6	390
PP & PE film in rolls, stacked 14 ft high	550
Methyl alcohol	65
Gasoline	290
Kerosene	290
Diesel oil	175

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

Table B-3 Maximum Heat Release Rates

$Q_m = qA$

where:

Q_m = maximum heat release rate (Btu/sec)

q = heat release density (Btu/sec/ft^2)

A = floor area (ft^2)

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)
Wood pallets, stacked 1 $^1/_2$ ft high (6-12% moisture)	150-310	110	m-f
Wood pallets, stacked 5 ft high (6-12% moisture)	90-190	330	f
Wood pallets, stacked 10 ft high (6-12% moisture)	80-110	600	f
Wood pallets, stacked 16 ft high (6-12% moisture)	75-105	900	f
Mail bags, filled, stored 5 ft high	190	35	f
Cartons, compartmented, stacked 15 ft high	60	200	*
Paper, vertical rolls, stacked 20 ft high	15-28	–	*
Cotton (also PE, PE/Cot, Acrylic/Nylon/PE), garments in 12-ft high rack	20-42	–	*
Cartons on pallets, rack storage, 15-30 ft high	40-280	–	m-f
Paper products, densely packed in cartons, rack storage, 20 ft high	470	–	m-s
PE letter trays, filled, stacked 5 ft high on cart	190	750	f
PE trash barrels in cartons stacked 15 ft high	55	250	*
FRP shower stalls in cartons, stacked 15 ft high	85	110	*
PE bottles packed in Item 6	85	550	*
PE bottles in cartons, stacked 15 ft high	75	170	*
PE pallets, stacked 3 ft high	130	–	f

Table B-3 Maximum Heat Release Rates *(continued)*

PE pallets, stacked 6-8 ft high	30-55	–	*
PU mattress, single, horizontal	110	–	f
PF insulation, board, rigid foam, stacked 15 ft high	8	170	*
PS jars packed in Item 6	55	1200	*
PS tubs nested in cartons, stacked 14 ft high	105	450	f
PS toy parts in cartons, stacked 15 ft high	110	180	f
PS insulation board, rigid, stacked 14 ft high	7	290	*
PVC bottles packed in Item 6	9	300	*
PP tubs packed in Item 6	10	390	*
PP and PE film in rolls, stacked 14 ft high	40	350	*
Distilled spirits in barrels, stacked 20 ft high	23-40	–	*
Methyl alcohol	–	65	–
Gasoline	–	200	–
Kerosene	–	200	–
Diesel Oil	–	180	–

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

Table B-4 Maximum Heat Release Rates from Fire Detection Institute Analysis

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

Table B-5 Characteristics of Ignition Sources [3]

	Typical Heat Output (w)	Burn Time[a] (sec)	Maximum Flame Height (mm)	Flame Width (mm)	Maximum Heat Flux (kW/m^2)
Cigarette 1.1 g (not puffed, laid on solid surface), bone dry, conditioned to 50%	5	1200	–	–	42
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 waste-basket, 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 sec
[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/sec = 1.055 W
1 oz = 0.02835 kg = 28.35 g
1 Btu/ft^2-sec = 11.35 kW/m^2

Table B-6 Characteristics of Typical Furnishings as Ignition Sources [3]

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

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

Table B-7 Heat Release Rates of Chairs in Recent NBS Tests [3]

Specimen	Mass (kg)	Combustible (kg)	Style	Frame	Padding	Fabric	Interliner	Peak m (g/sec)	Peak q (kW)
C12	17.9	17.0	traditional easy chair	wood	cotton	nylon	–	19.0	290[a]
F22	31.9		traditional easy chair	wood	cotton (FR)	cotton	–	25.0	370
F23	31.2		traditional easy chair	wood	cotton (FR)	olefin	–	42.0	700
F27	29.0		traditional easy chair	wood	mixed	cotton	–	58.0	920
F28	29.2		traditional easy chair	wood	mixed	cotton	–	42.0	730
CO2	13.1	12.2	traditional easy chair	wood	cotton, PU	olefin	–	13.2	800[b]
CO3	13.6	12.7	traditional easy chair	wood	cotton, PU	cotton	–	17.5	460[a]
CO1	12.6	11.7	traditional easy chair	wood	cotton, PU	cotton	–	17.5	260[a]
CO4	12.2	11.3	traditional easy chair	wood	PU	nylon	–	75.7	1350[b]
C16	19.1	18.2	traditional easy chair	wood	PU	nylon	neoprene	NA	180
F25	27.8		traditional easy chair	wood	PU	olefin	–	80.0	1990
T66	23.0		traditional easy chair	wood	PU, polyester	cotton	–	27.7	640
F21	28.3		traditional easy chair	wood	PU (FR)	olefin	–	83.0	1970
F24	28.3		traditional easy chair	wood	PU (FR)	cotton	–	46.0	700
C13	19.1	18.2	traditional easy chair	wood	PU	nylon	neoprene	15.0	230[a]
C14	21.8	20.9	traditional easy chair	wood	PU	olefin	neoprene	13.7	220[a]
C15	21.8	20.9	traditional easy chair	wood	PU	olefin	neoprene	13.1	210[b]
T49	15.7		easy chair	wood	PU	cotton	–	14.3	210
F26	19.2		thinner easy chair	wood	PU (FR)	olefin	–	61.0	810
F33	39.2		traditional loveseat	wood	mixed	cotton	–	75.0	940
F31	40.0		traditional loveseat	wood	PU (FR)	olefin	–	130.0	2890
F32	51.5		traditional sofa	wood	PU (FR)	olefin	–	145.0	3120
T57	54.6		loveseat	wood	PU, cotton	PVC	–	61.9	1100
T56	11.2		office chair	wood	latex	PVC	–	3.1	80
CO9/T64	16.6	16.2	foam block chair	wood (part)	PU, polyester	PU	–	19.9	460
CO7/T48	11.4	11.2	modern easy chair	PS foam	PU	PU	–	38.0	960
C10	12.1	8.6	pedestal chair	rigid PU foam	PU	PU	–	15.2	240[a]
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	–	polystyr-ene	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/sec = 0.4536 kg/sec = 453.6 g/sec
1 lb = 0.4536 kg
1 Btu/sec = 1.055 kW

Table B-8 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/sec = 1.055 kW

Table B-9 Effect of Padding Type on Maximum Heat Release Rate in Table B-7(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/sec = 1.055 kW

Table B-10 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/sec = 1.055 kW

Table B-11 Considerations for Selecting Heat Release Rates for Design

Constant Heat Release Rate Fires		
Theobald (industrial)	260 kW/m^2	(approx. 26 Btu/sec-ft^2)
Law (offices)	290 kW/m^2	(approx. 29 Btu/sec-ft^2)
Hansell & Morgan (hotel rooms)	249 kW/m^2	(approx. 25 Btu/sec-ft^2)
Variable Heat Release Rate Fires		
NBSIR 88-3695 Fuel Configuration	**Fire Growth Rate**	
Computer Work Station free burn compartment	slow-fast very slow	
Shelf Storage free burn	medium up to 200 sec, fast after 200 sec	
Office Module	very slow-medium	
NISTIR 483 Fuel Commodity	**Peak Heat Release Rate (kW)**	
Computer Work Station	1000-1300	
NBS Monograph 173 Fuel Commodity	**Peak Heat Release (kW)**	
Chairs	80-2480 (<10, metal frame)	
Loveseats	940-2890 (370, metal frame)	
Sofa	3120	

Appendix C T-Squared Fires

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

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

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 might or might not actually produce a t-squared curve. The tacit assumption is that the t-squared approximation is close enough for reasonable design decisions.

Figure C-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 can be a serious detriment to the use of the t-squared approximation. In most instances this is not a serious concern in the atria and other large spaces covered by this guide. It is expected that the rate of heat release during the incubation period would not usually be sufficient to cause activation of the smoke detection system. In any case where such activation happens or human observation results in earlier activation of the smoke management system, a fortuitous safeguard would result.

Figure C-2, 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.

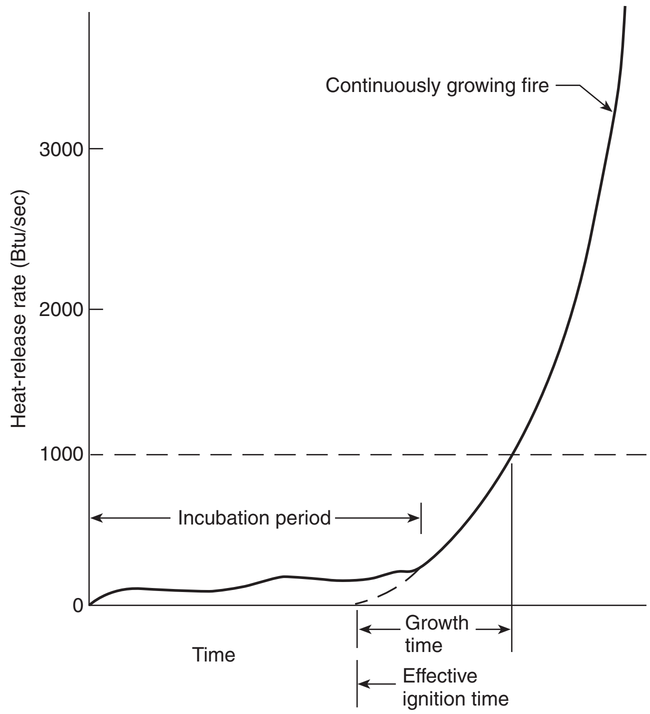

Figure C-1 Conceptual illustration of continuous fire growth.

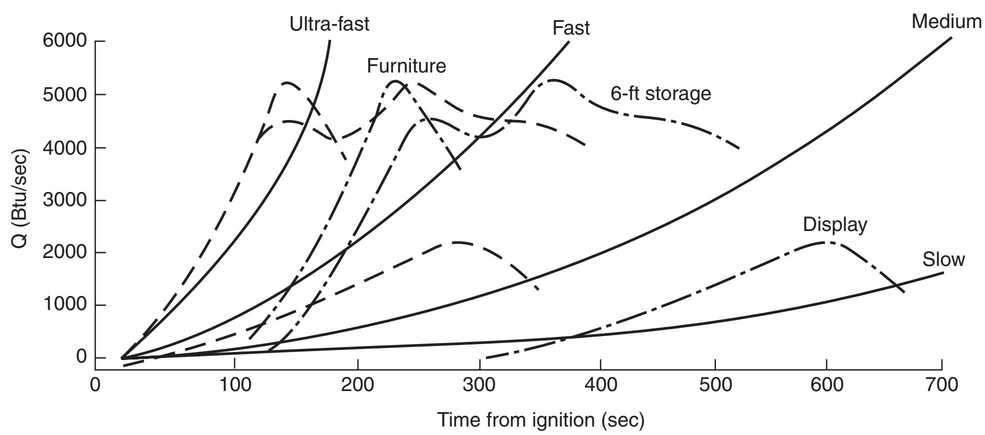

Figure C-2 T-squared fire, rates of energy release.