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NFPA 204M
Smoke and Heat Venting
1985

NFPA®

National Fire Protection Association Batterymarch Park, Quincy, MA 02269

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Policy Adopted by NFPA Board of Directors on December 3, 1982

The Board of Directors reaffirms that the National Fire Protection Association recognizes that the toxicity of the products of combustion is an important factor in the loss of life from fire. NFPA has dealt with that subject in its technical committee documents for many years.

There is a concern that the growing use of synthetic materials may produce more or additional toxic products of combustion in a fire environment. The Board has, therefore, asked all NFPA technical committees to review the documents for which they are responsible to be sure that the documents respond to this current concern. To assist the committees in meeting this request, the Board has appointed an advisory committee to provide specific guidance to the technical committees on questions relating to assessing the hazards of the products of combustion.

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NFPA 204M

Guide for

Smoke and Heat Venting

1985 Edition

This edition of NFPA 204M, *Guide for Smoke and Heat Venting*, was prepared by the Technical Committee on Building Construction, released by the Correlating Committee on Building Construction, and acted on by the National Fire Protection Association, Inc. at its Annual Meeting held May 13-17, 1985 in Chicago, Illinois. It was issued by the Standards Council on June 6, 1985, with an effective date of June 26, 1985, and supersedes all previous editions.

The 1985 edition of this guide 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 204M

This project was initiated in 1956 when the NFPA Board of Directors referred the subject to the Committee on Building Construction. A Tentative Guide was submitted to NFPA in 1958. Revised and tentatively adopted in 1959 and again in 1960, the guide was officially adopted in 1961. In 1968, a revised edition was adopted which included a new section on Inspection and Maintenance.

In 1975, a reconfirmation action failed as concerns over use of the guide in conjunction with automatic sprinklered buildings had surfaced. Because of this controversy, work on a revision to the guide continued at a slow pace.

The Technical Committee and Subcommittee members agreed that the state of the art has progressed sufficiently to develop improved technologically based criteria for design of venting and, therefore, the 1982 edition of the document represented a major advance in engineered smoke and heating venting, although reservations over vent/sprinkler applications still existed.

At the time this guide was formulated, the current venting theory was considered unwieldy for this format and, consequently, the more adaptable theory as described herein was adopted. Appreciation must be extended to Dr. Gunnar Heskestad at the Factory Mutual Research Corporation for his major contribution to the theory applied in this guide, which is detailed in Appendix A.

This 1985 edition again revises Chapter 6 on the subject of venting in sprinklered buildings. Test data from work done at the Illinois Institute of Technology Research Institute, which had been submitted to the Committee as part of a public proposal, did not permit consensus to be developed whether sprinkler control was impaired or enhanced by the presence of automatic roof vents of typical spacing and area. The revised wording of Chapter 6 encourages the designer to use the available tools and data referenced in the document while the use of automatic venting in sprinklered buildings is under review.

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Alternates

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NFPA 204M

Guide for

Smoke and Heat Venting

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Chapter 1 General Information

1-1 Importance.

1-1.1 Since the end of World War II there has been a general trend toward the construction of large industrial and storage buildings with extensive undivided floor areas. In many cases, large undivided floor areas are necessary for the functional operation of the building. One result, from a fire protection viewpoint, has been the increased potential for large loss fires involving extensive individual fire areas. To a great extent, this tendency has been offset through the increased use of automatic sprinkler protection.

1-1.2 Furthermore, large undivided floor areas present extremely difficult fire fighting problems, since the fire department must enter these areas in order to combat fires in central portions of the building. If the fire department is unable to enter because of the accumulation of heat and smoke, fire fighting efforts may be reduced to a futile application of hose streams to perimeter areas while fire consumes the interior. Windowless buildings also present similar fire fighting problems. One fire protection tool which may be a valuable asset for fire fighting operations in such buildings is smoke and heat venting. Guidance is provided herein relative to the use of smoke and heat venting.

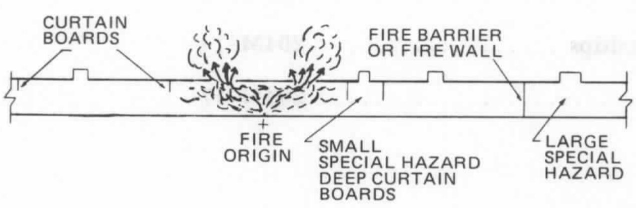


Figure 1-1 Behavior of Combustion Products Under Vented and Curtained Roof.

1-1.3 Two different types of guidance are provided. The first has to do with the venting of limited-growth fires. These are fires which are not expected to grow beyond a predictable heat-release rate. By following the recommendations in the case of limited-growth fires, containment of the effects of the fire to the upper volume of the curtained area of fire origin can be anticipated as long as the building construction remains intact. The second type of guidance is relevant to the venting of fires which, if unchecked, will continue to grow to some unknown size. For this type of continuous-growth fire, the specific guidance provided allows one to establish a minimum predictable design time during which (a) the effects of the fire will be confined to the curtained area, and (b) visibility up to a design-elevation above the floor of the curtained area will be maintained. This minimum clear-visibility design time will facilitate such activities as locating the fire, appraising the fire severity and extent, evacuating the building, and making an informed decision on deployment of personnel and equipment to be used for fire fighting. The minimum clear-visibility design time is measured from the time the first vents activate.

1-1.4 Vents are not a substitute for sprinklers or other extinguishing facilities.

1-2 Application and Scope.

1-2.1 Provisions of Section 1-3 through 4-4.3 are intended to offer guidance in the design of facilities for the emergency venting of products of combustion from uncontrolled fires in nonsprinklered, single-story buildings. Information regarding venting in sprinklered buildings is included in Chapter 6. The provisions do not attempt to specify under what conditions venting must be provided as this is dependent upon an analysis of the individual situation.

1-2.2 The provisions of this guide may be applied to the top story of multiple-story buildings. There are many features that would be difficult or impractical to incorporate into the lower stories of such buildings.

1-2.3 This guide does not apply to other ventilation (or lighting, as may be the case with monitors and skylights) designed for regulation of temperature within a building, for personnel comfort or production equipment cooling, or to venting provided for explosion pressure relief (*see NFPA 68, Guide for Explosion Venting*).

1-2.4 Building construction of all types is included.

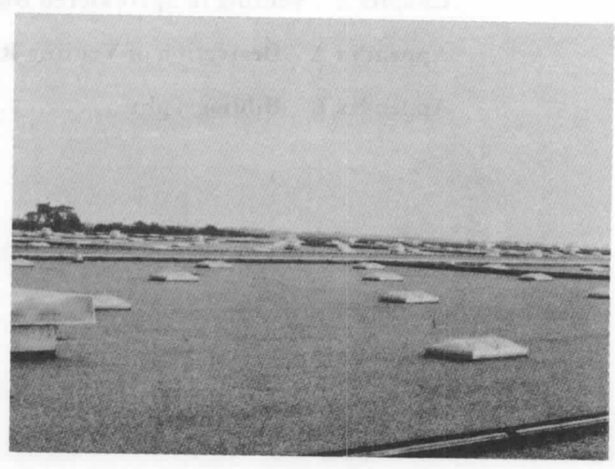


Figure 1-2 Plant with Roof Vents.

1-2.5 The concepts set forth in this guide were developed for venting fires in large undivided floor areas with ceiling heights sufficient to allow the design fire plume and smoke layer to develop [normally, 15 ft (4.57 m) or greater]. Such conditions are frequently encountered in industrial and storage buildings. The information in Chapter 4 relative to fire growth was specifically developed for these occupancies. The application of these concepts to buildings of other occupancies or lower ceiling heights requires careful engineering judgment.

1-3 Principles of Venting.

1-3.1 The following is a description of the significant phenomena which occur during a fire when a fire venting strategy is implemented:

(a) Due to buoyancy, hot gases rise vertically from the combustion zone and then flow horizontally below the roof until blocked by a vertical barrier (a wall or draft curtain), thus initiating a layer of hot gases below the roof.

(b) The volume and temperature of gases to be vented are a function of the rate of heat release of the fire and the amount of air entrained into the buoyant plume produced.

(c) The depth of the layer of hot gases increases, the fire continues to grow, and the layer temperature continues to rise until vents operate.

(d) Operation of vents within a curtained area will enable some of the upper layer of hot gases to escape, and slow the rate of deepening of the layer of hot gases. With sufficient venting area, the rate of deepening of the layer can be arrested and even reversed. The rate of discharge through a vent of given area is primarily determined by the depth of the layer of hot gases and its temperature. Adequate quantities of replacement inlet air from low level air inlets are required if the products of combustion-laden upper gases are to escape according to design.

1-3.2 The heat-release rate of the fire is the basis by which all the phenomena of 1-3.1 can be computed. In this regard, this guide is based on an appropriate characterization of the fire's growth potential per Tables 4-1 and 4-2. Once such a characterization is made and subsequent design guides are implemented, the desired benefits described in 1-1.3 can be anticipated.

1-4 Classification of Occupancies.

1-4.1 Tests and studies provide a basis for division of occupancies into classes depending upon the fuel available for contribution to fire. There is a wide variation in the quantities of combustible materials in the many kinds of industrial plants and also between various buildings and areas of most individual plants. Classification should take into account the average or anticipated fuel loading and the rate of heat release anticipated from the combustible materials or flammable liquids contained therein.

1-4.2 To assist in quantifying the type of fire in occupancies of interest, Table 4-1 presents characteristic heat-release rates for limited-growth fires, and Table 4-2 presents characteristic growth times for continuous-growth fires, in a variety of different types of fuel arrays.

1-4.3 It is to be recognized that many plants will have buildings or areas with different fire hazards. Accordingly, venting facilities may be designed for the appropriate fire growth characteristics as discussed in this guide.

Chapter 2 Vents

2-1 Types of Vents.

2-1.1 Experience has shown that any opening in a roof, over a fire, will relieve some heat and smoke. However, building designers and fire protection engineers cannot rely on casual inclusion of skylights, windows or monitors as adequate venting means. Standards now exist (Underwriters Laboratory, Factory Mutual) that include design criteria and test procedures for unit vents that call for simulated fire tests as well as engineering analysis.

2-1.2 The guides and tables in this document are based on automatic operating vents as the result of activation of a heat-responsive device rated at 100°F (37.8°C) to 220°F (104.4°C) above ambient having a time constant of not more than 233 seconds at 5 ft (1.53 m) per second gas velocity with such a device fitted to each vent.

2-1.3 An alternate mode of operation, whether by heat, smoke or other method, may be tailored to the hazard so long as the accepted system will operate at least as fast as the above noted heat-responsive device and is either listed, or proven to be equivalent by satisfactory data or by engineering analysis.

2-2 Vent Design Constraints.

2-2.1 Materials of construction and methods of installation must be used appropriately to resist expected extremes of temperature, wind, building movement, rain, hail, snow, ice, sunlight, corrosive environment, internal and external dust, dirt, and debris. Compatibility between the vent mounting elements and the building structure to which they are attached must be assured (holding power, electrochemical interaction, wind lift, building movement, etc.).

2-2.2 Vents designed to have multiple functions (daylighting, roof access, comfort ventilation, etc.) require maintenance of the fire protection function that might be impaired by the other uses. These may include loss of spring tension, racking or wear of moving parts, adverse exterior cooling effects on the fire protection release mechanism, adverse changes in performance sequence such as premature heat actuation leading to vent opening, or reduced sensitivity to heat.

2-2.3 To avoid inadvertent operation, it is important that the actuating element be selected with regard to the expected full range of ambient conditions.

2-2.4 Vents may be single unit (entire unit opens fully with a single sensor) or multiple units in rows, clusters, groups, or other arrays that will satisfy the venting requirements for the specific hazard.

2-2.5 If the hazard is localized (dip tank, solvent storage, etc.), it is preferable for the vents to be located directly above such hazard.

2-2.6 It is essential that the specific vent mechanism and structure (or a representative modular section) be arranged to be easily inspected.

2-2.7 Remote or programmed operation of vents may be used to complement, but not replace or impair, individual automatic sensor actuation.

2-3 Methods of Operation.

2-3.1 An "automatic" mechanism for opening the roof vents is desirable for effective release of heat, smoke, and gaseous by-products. If excessive smoke is likely to be generated prior to the release of sufficient heat to open vents, smoke detectors with appropriate linkages to open vents may be preferred.

2-3.2 Automatic actuation and operation need to have a minimum of "failure points" (any one of which could impair the vent). If "failure" of a component occurs, it will preferably lead to an "open vent" condition as a less hazardous mode than a "non-opening" condition if a fire occurs. Gravity as a source of "force to open" is preferred, with assurance that such a mechanism is not easily blocked by snow or roof debris or internal projections. Alternate opening mechanisms need to be approved as to reliability of performance and estimated useful life.

2-3.3 All automatic vents should also be designed to open by manual means.

2-3.4 To be effective, latching mechanisms need to be jam-proof, corrosion-resistant, and resistant to pressure differentials arising from windstorms, process operations, overhead doors, or traffic vibrations.

2-3.5 The fact that hot or cold exterior winds penetrating and adversely affecting the heat-actuated sensors may have an adverse effect on the "automatic" response of the vent to an interior fire, necessitates a critical analysis of specific installations of fixed or operating louvers, shutters, or dampers into the overall venting system.

2-4 Dimensioning and Spacing of Vents. The dimensioning and spacing of vents are considered to be effective when the following criteria are met:

(a) The area of a unit vent or cluster does not exceed $2d^2$, where d is the depth of the curtain board or the design depth of the smoke layer. These depths are measured from the center line of the vent. (*See Figure 3-1.*)

(b) The width of the monitor does not exceed the depth of the curtain board d, or the design depth of the smoke layer when curtains are not provided.

(c) The vent spacing does not exceed an arrangement such that on plan the distance between any point on the floor and the nearest vent, all within the curtained area, does not exceed 2.8H (the diagonal of a square whose side is 2H), where H is the ceiling height. (*Also see Figure 3-1.*)

(d) The total vent area per curtain compartment under the ceiling depends on the severity of the expected fire, which is discussed in Chapter 4.

(e) Where mechanical vents are considered, the total suggested vent area may be replaced by "total exhaust flow."

Chapter 3 Curtain Boards

3-1 General.

3-1.1 Curtain boards are important for prompt and positive activation of the vents because they bank up heat in the curtained area.

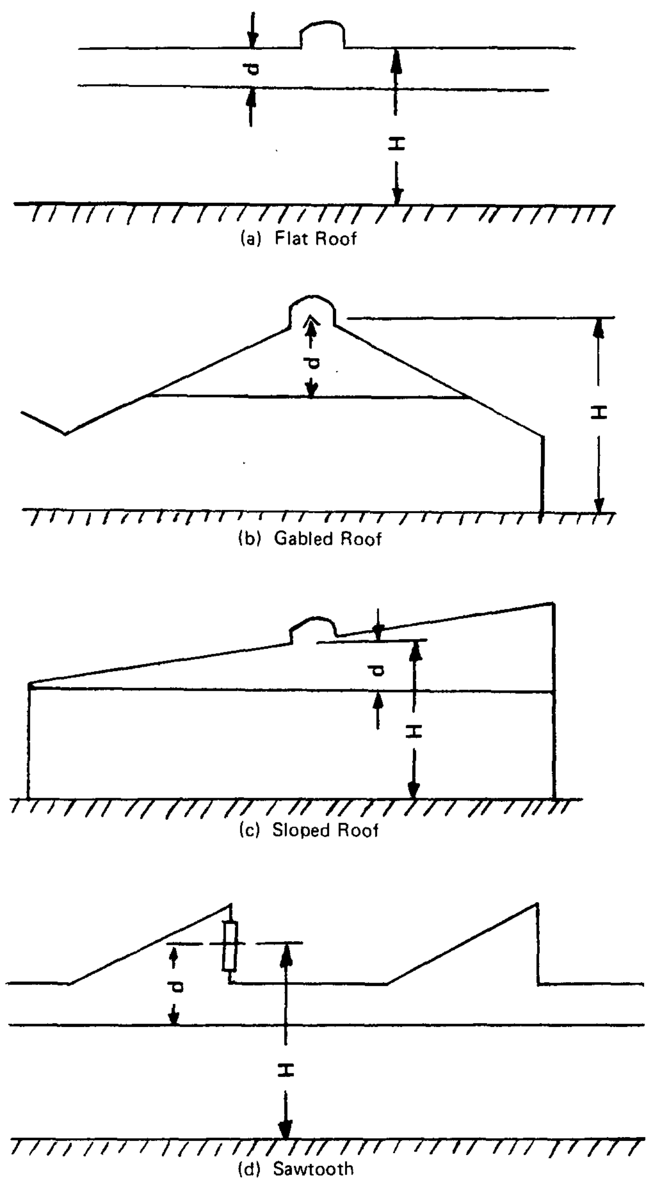


Figure 3-1 Measurement of Ceiling Height (H) and Curtain Depth (d).

3-1.2 Curtain boards serve to limit the spread of heat and smoke beneath the ceiling during design duration of the venting system.

3-2 Construction. It is desirable that curtain boards be made of any substantial, noncombustible material that will resist the passage of smoke.

3-3 Location and Depth.

3-3.1 Curtain boards, where provided, should extend down from the ceiling for a sufficient distance to assure that the value of d as shown in Figure 3-1 is a minimum of 20 percent of ceiling height (H) where H is:

(a) For flat roofs, measured from ceiling to floor.

(b) For sloped roofs, measured from center of vent to the floor.

NOTE: See Figure 3-1. When d exceeds 20 percent of H, it is desirable that H ± d not be less than 10 ft (3.05 m).

3-3.2 Around special hazards, the curtain should preferably extend down to within approximately 10 ft (3.05 m) from the floor.

If, however, the hazard is located more than 10 ft (3.05 m) above the floor, the depth of the curtain board may need to be decreased to allow for effective application of fire fighting appliances, provided that the basic criteria for venting included in this guide are observed.

3-4 Spacing.

3-4.1 The distance between curtain boards should not exceed 8 times the ceiling height to ensure that vents remote from the fire within the curtained compartment will be effective.

3-4.2 Smaller curtained areas may be desirable where occupancies are particularly vulnerable to damage. However, it is important that the distance between curtain boards not be less than 2 times the ceiling height, unless the curtain boards extend down to a depth of at least 40 percent of the ceiling height.

Chapter 4 Installed Vent Area or Exhaust Capacity

4-1 General.

4-1.1 Curtained Compartments.

4-1.1.1 It is essential that curtained compartments, or the ceiling area of buildings requiring no curtain boards, be furnished with a total installed vent area (or exhaust capacity in case of mechanical ventilation) sufficient to vent fires of the expected severity.

4-1.1.2 In addition to the expected fire severity, the installed vent area (or exhaust capacity) will depend on the depth of the curtain boards or the design depth of the smoke layer.

4-1.1.3 Unless the occupancy or hazard is such that the expected fire will peak or level off at a predictable maximum size, the installed vent area (or exhaust capacity) will also depend on the minimum clear-visibility design time (*see 1-1.3*) as measured from the time the first vents activate.

4-1.2 Recommended vent areas per curtained compartment have been established for two general classes of fires:

4-1.2.1 *Limited-Growth Fires* include those which are not expected to grow past a predictable maximum size, such as special hazard fires.

4-1.2.2 *Continuous-Growth Fires* include those which can be expected to grow indefinitely until intervention by fire fighters.

4-1.3 The recommended vent areas (installed vent areas) are based on the assumption that the aerodynamic discharge coefficient of the vents is 0.6, which is normal for commercial gravity vents. If the discharge coefficient is different from 0.6, the recommended vent areas need to be multiplied by the ratio of 0.6 to the actual discharge coefficient.

4-1.4 For mechanical venting systems capable of functioning under the expected fire exposure, recommended exhaust capacities per curtained compartment are obtained by simple conversion from the recommended vent areas per curtained compartment. The conversion depends on the depth of the curtain board, or the design depth of the smoke layer, in the following manner:

Curtain Depth (ft)	Mechanical Exhaust Capacity per Unit Area of Gravity Vent (SCFM/ft²)
6	354
8	409
10	457
12	501
16	578
20	647
24	708

NOTE: SCFM = Standard Cubic Feet per Minute (Standard Temperature and Pressure).

For SI Units: 1 ft = .3048 m; 1 ft² = .0929 m².

4-2 Limited-Growth Fire.

4-2.1 Recommended Vent Area.

4-2.1.1 Recommended vent areas per curtained compartment (in sq ft) are plotted in Figure 4-1 against the expected maximum heat-release rate (in Btu/second) of the combustibles underneath the curtained compartment. The figure pertains to a curtain depth which is 20 percent of the ceiling height. For each ceiling height, the respective curve begins at a heat-release rate where vents whose operating device is defined by 2-1.2 are first expected to be useful.

4-2.1.2 Furthermore, for each ceiling height, the respective curve terminates near a heat-release rate beyond which the feasibility of the venting approach recommended in this guide might be questioned ($Q_{feasible}$).

4-2.1.3 Along the dashed segment of the curves, gas temperatures in excess of 1000°F (537.7°C) will be reached; unprotected structural steel may begin to lose strength and flashover may occur within the curtained area. The lowest rate of heat release at which this occurs is referred to as Q_{1000}.

4-2.1.4 For curtain depths greater than 20 percent of the ceiling height, the vent areas read from Figure 4-1 may be multiplied by the following factors:

Curtain Depth in Percent of Ceiling Height	Multiplication Factor
30	0.71
40	0.53
50	0.40
60	0.29
70	0.20
80	0.13

For SI Units: 1 ft = .3048 m.

Table 4-1 Limited-Growth Fires.

Heat-release rate per unit floor area of fully involved combustibles, assuming 100 percent combustion efficiency.
(PE = polyethylene; PS = polystyrene; PVC = polyvinyl chloride; PP = polypropylene; PU = polyurethane; FRP = Fiberglass-Reinforced Polyester)

Btu/sec per ft² of Floor Area

1. Wood pallets, stack 1 ½ ft high (6-12% moisture)
2. Wood pallets, stack 5 ft high (6-12% moisture)
3. Wood pallets, stack 10 ft high (6-12% moisture)
4. Wood pallets, stack 16 ft high (6-12% moisture)
5. Mail bags, filled stored 5 ft high
6. Cartons, compartmented, stacked 15 ft high
7. PE letter trays, filled, stacked 5 ft high on cart
8. PE trash barrels in cartons, stacked 15 ft high

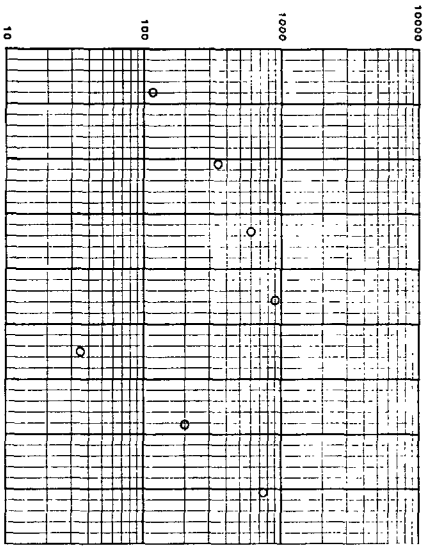
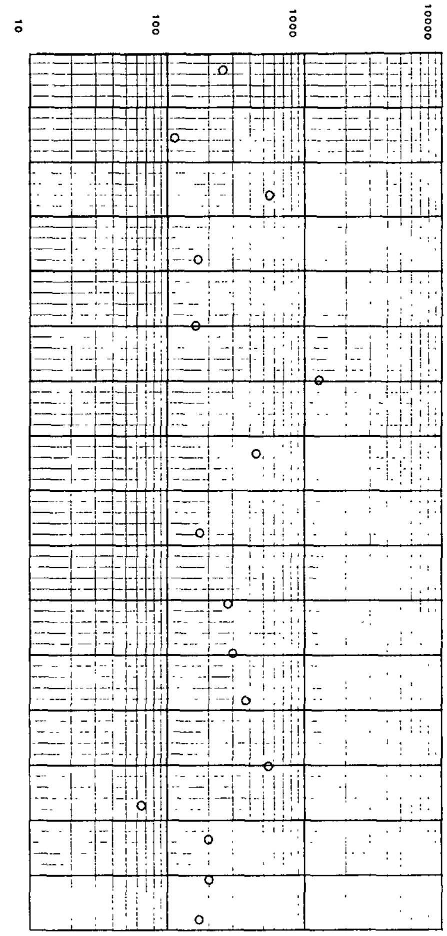


Table 4-1 Continued.

9. FRP shower stalls in cartons, stacked 15 ft high
10. PE bottles packed in Item 6
11. PE bottles in cartons, stacked 15 ft high
12. PU insulation board, rigid foam, stacked 15 ft high
13. PS jars packed in Item 6
14. PS tubs nested in cartons, stacked 14 ft high
15. PS toy parts in cartons, stacked 15 ft high
16. PS insulation board, rigid foam, stacked 14 ft high
17. PVC bottles packed in Item 6
18. PP tubs packed in Item 6
19. PP and PE film in rolls, stacked 14 ft high
20. Methyl alcohol
21. Gasoline
22. Kerosene
23. Diesel oil



For SI Units: 1 ft = .3048 m; 1 ft² = 0.929 m².

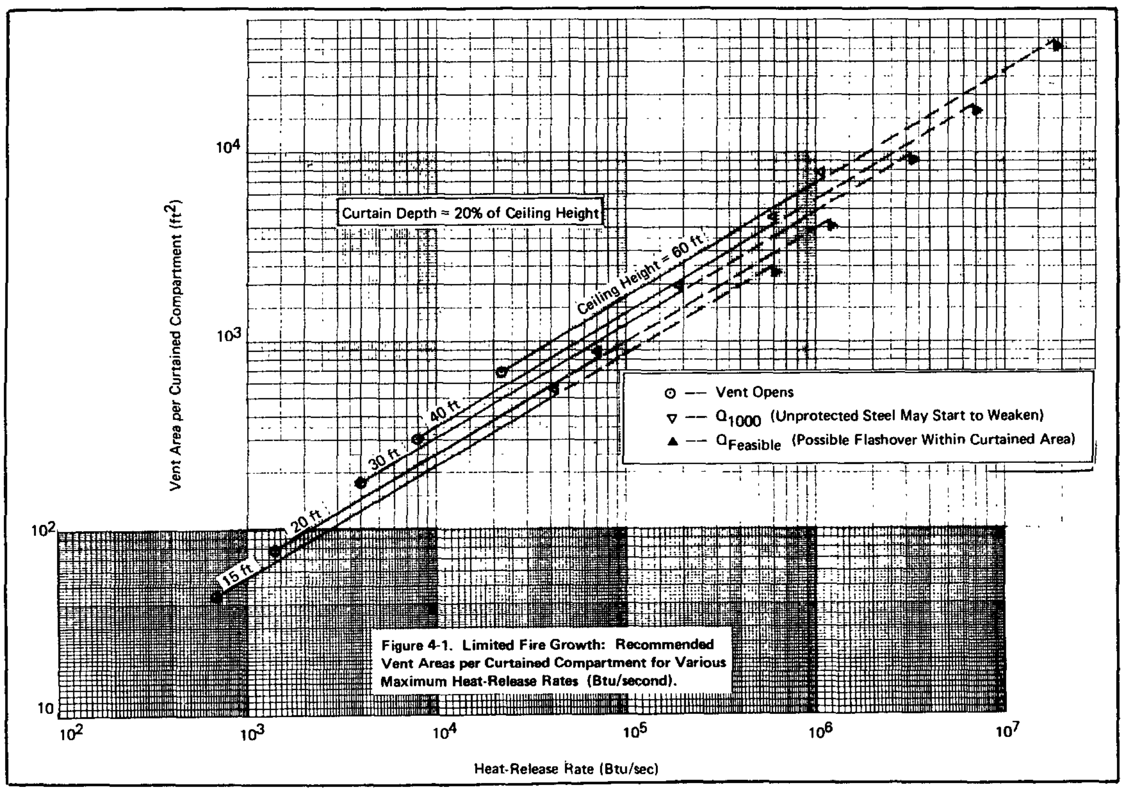


Figure 4-1. Limited Fire Growth: Recommended Vent Areas per Curtained Compartment for Various Maximum Heat-Release Rates (Btu/second).

For SI Units: 1 in. = 25.4 mm; 1 ft² = .093 m²; 1 Btu/sec = 1.054 kw.

4-2.1.4.1 For curtain depths greater than 20 percent of the ceiling height, the heat-release rate where gas temperatures in excess of 1000°F (537.7°C) may occur, Q_{1000}, can be estimated from the following equation (where H is the ceiling height in ft and d is the curtain board depth in ft):

$$Q_{1000}\ (\text{BTU/sec}) = 69\ (H - d)^{5/2}$$

4-2.1.4.2 For curtain depths greater than 20 percent of the ceiling height, the heat-release rate beyond which venting may not be feasible according to the venting approach in this guide, $Q_{feasible}$, can be estimated from:

$$Q_{feasible}\ (\text{BTU/sec}) = 1130\ (H - d)^{5/2}$$

4-2.2 Vent areas per curtained compartment, determined according to 4-2.1.1 and 4-2.1.4, are to be sized and distributed within the constraints of 2-4.1.

4-2.3 Consult Table 4-1 for examples of heat-release rate data. Most of these data pertain to fairly high storage. For lower storage heights, it may be assumed that heat-release rate is proportional to storage height. Larger storage heights should be extrapolated with caution.

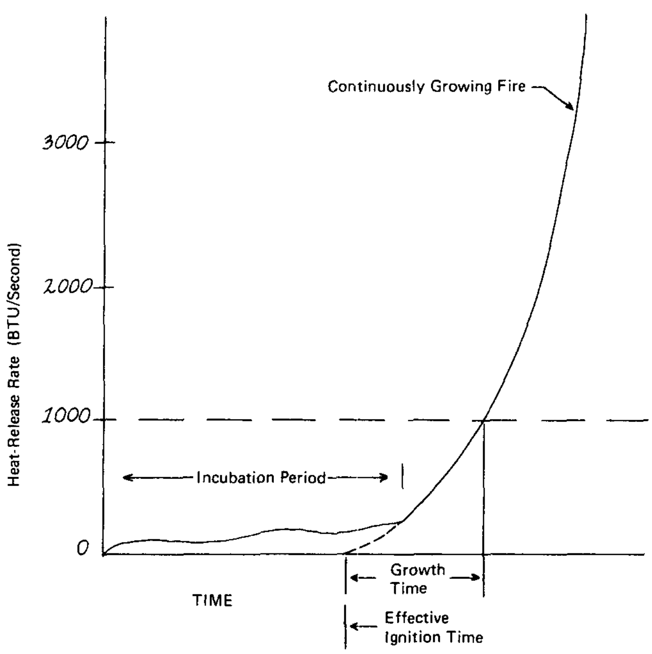


Figure 4-2 Conceptual Illustration of Continuous Fire Growth.

4-3 Continuous-Growth Fire.

4-3.1 Recommended Vent Area.

4-3.1.1 Starting after an incubation period, the heat-release rate of these fires grows continuously proportional to the square of time. The growth time of a given fire is defined as the interval of time between the effective ignition time and the time when the fire reaches an intermediate energy release rate of 1000 BTU/sec. (*See Figure 4-2 and Table 4-2.*)

4-3.1.2 Recommended vent areas per curtained compartment depend on the ceiling height (H) and the growth time (*see 4-3.1.1*). They also depend on the spacing of curtain boards (S_c), the vent spacing and means of vent activation, as well as the desired minimum clear-visibility design time from the time the first vents activate.

4-3.1.3 Recommended vent areas per curtained compartment are listed in Table 4-3 for the minimum recommended curtain depth of 20 percent of ceiling height (*see 3-3.1*) and for vents spaced at no more than one half of the curtain board spacing. For other than square curtains, the spacing S_c is interpreted as the largest spacing defined by the curtained area.

4-3.1.4 The tabulated areas are approximate, pertaining to vents that are operated by heat-responsive devices of average thermal inertia and rated between 100°F (37.8°C) and 220°F (104.4°C) above the ambient temperature. Each entry in Table 4-3 gives the range of vent areas [in 1000 ft² (90 m²)] associated with the selected range of temperature ratings.

4-3.1.5 Entries boxed in are not possible (since the vent areas exceed the largest possible curtained area of $S_c \times S_c$); however, these entries may be needed for curtain depths greater than 20 percent of ceiling height as treated in 4-3.1.9.

4-3.1.6 Where values are not given in Table 4-3, heat-release rates are greater than $Q_{feasible}$. (*See 4-2.1.1 and 4-2.1.4.*)

4-3.1.7 Entries in parentheses correspond to levels of heat release greater than Q_{1000}. (*See 4-2.1.1 and 4-2.1.4.*)

4-3.1.8 To illustrate use of the table, consider an installation with heat-responsive devices rated approximately 100°F (37.8°C) above ambient, a ceiling height of 20 ft (6.1 m), a growth time of 150 seconds, a curtain spacing of 80 ft (24.4 m) ($S_c = 4 \times H$), and a minimum clear-visibility design time of 10 minutes; the lower limit 100°F (37.8°C) of the appropriate entry in Table 4-1 indicates a vent area per curtained compartment of $0.64 \times 1000 = 640$ ft² (59.5 m²) for this case.

4-3.1.9 The recommended vent area per curtained compartment is reduced if larger curtain depths than minimum (20 percent of ceiling height) are installed. The reduced areas are calculated by multiplying the values listed in Table 4-3 by the appropriate multiplication factor listed in 4-2.1.4, depending on curtain depth.

4-3.2 The maximum vent area in any compartment need not exceed the vent area recommended for a limited-growth fire of all the combustibles beneath the curtained area calculated in accordance with Section 4-2 of this guide.

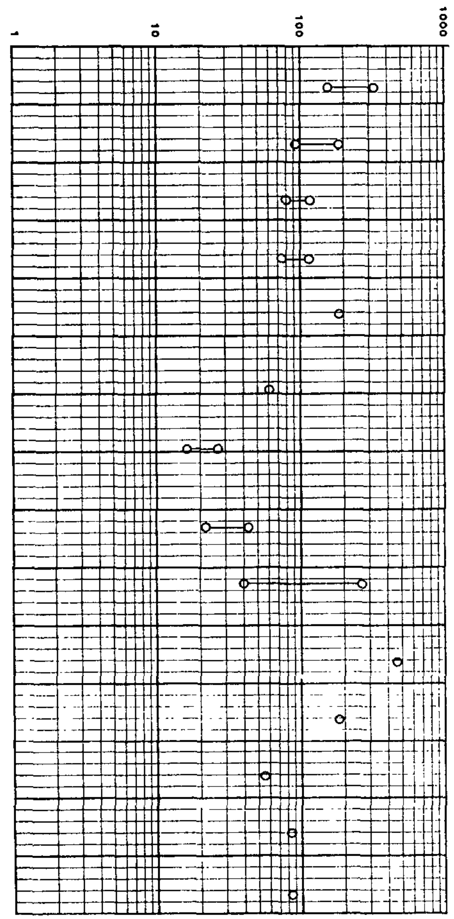
4-3.2.1 To determine if Notes 4 or 6 from Table 4-3 apply to the newly derived values for vent areas, it is necessary to determine the relationship of the vent areas associated with Q_{1000} and $Q_{feasible}$.

Table 4-2 Continuous-Growth Fires.

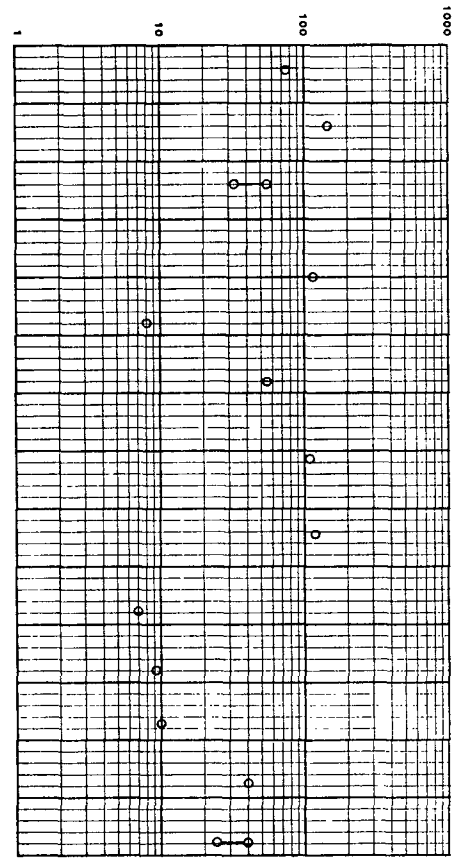
Growth times of developing fires in various combustibles, assuming 100 percent combustion efficiency. (*See 4-3.1.1 for definition of growth time.*)

(PE = polyethylene; PS = polystyrene; PVC = polyvinyl chloride; PP = polypropylene; PU = polyurethane; FRP = Fiberglass-Reinforced Polyester)

1. Wood pallets, stack 1 ½ ft high (6-12% moisture)
2. Wood pallets, stack 5 ft high (6-12% moisture)
3. Wood pallets, stack 10 ft high (6-12% moisture)
4. Wood pallets, stack 16 ft high (6-12% moisture)
5. Mail bags, filled, stored 5 ft high
6. Cartons, compartmented, stacked 15 ft high
7. Paper, vertical rolls, stacked 20 ft high
8. Cotton (also PE, PE/Cot Acyrlic/Nylon/PE), garments in 12 ft high rack
9. "Ordinary combustibles" rack storage, 15-30 ft high
10. Paper products, densely packed in cartons, rack storage, 20 ft high
11. PE letter trays, filled, stacked 5 ft high on cart
12. PE trash barrels in cartons, stacked 15 ft high
13. FRP shower stalls in cartons, stacked 15 ft high
14. PE bottles packed in Item 6



15. PE bottles in cartons, stacked 15 ft high
16. PE pallets, stack 3 ft high
17. PE pallets, stacks 6-8 ft high
18. PU mattress, single, horizontal
19. PU insulation board, rigid foam, stacked 15 ft high
20. PS jars packed in Item 6
21. PS tubs nested in cartons, stacked 14 ft high
22. PS toy parts in cartons, stacked 15 ft high
23. PS insulation board, rigid foam, stacked 14 ft high
24. PVC bottles packed in Item 6
25. PP tubs packed in Item 6
26. PP and PE film in rolls, stacked 14 ft high
27. Distilled spirits in barrels, stacked 20 ft high



For SI Units: 1 ft = .3048 m; 1 ft² = .0929 m².

Table 4-3

Vent Area (in 1000 ft²) per Curtained Compartment for Heat-Responsive Device Operated Vents with Various Curtain Board Spacings (S_c) and Minimum Clear-Visibility Design Times (5, 10 or 15 minutes).

Ceiling Height, H	Growth Time (Sec)	$S_c = 2 \times H$ 5 min	$S_c = 2 \times H$ 10 min	$S_c = 2 \times H$ 15 min	$S_c = 4 \times H$ 5 min	$S_c = 4 \times H$ 10 min	$S_c = 4 \times H$ 15 min	$S_c = 8 \times H$ 5 min	$S_c = 8 \times H$ 10 min	$S_c = 8 \times H$ 15 min
15 ft	20				(1.9-2.1)			(2.2-2.5)		
	40	[.87-.97]			(.98-1.1)	(1.8-2.0)		(1.1-1.4)	(2.0-2.3)	
	80	(.44-.52)	(.82-.90)		(.52-.64)	(.90-1.0)	(1.3-1.4)	(.64-.83)	(1.0-1.2)	(1.5-1.7)
	150	.25-.32	(.43-.50)	(.63-.70)	.31-.41	(.50-.60)	(.70-.80)	(.41-.58)	(.60-.77)	(.81-.98)
	300	.15-.20	.23-.29	.32-.38	.20-.28	.28-.36	.37-.46	.27-.41	.36-.51	(.46-.61)
	600	.10-.14	.13-.18	.17-.23	.13-.21	.17-.25	.21-.29	.20-.34	.24-.38	.29-.43
20	20	[2.2-7.3]			(2.5-2.7)			(2.7-3.2)		
	40	(1.1-1.2)	[2.1-2.2]		(1.2-1.5)	(2.2-2.5)	(3.3-3.6)	(1.5-1.8)	(2.5-2.9)	(3.6-4.0)
	80	.56-.68	(1.0-1.1)	[1.5-1.6]	.68-.86	(1.1-1.3)	(1.6-1.8)	(.87-1.2)	(1.3-1.6)	(1.8-2.1)
	150	.34-.43	.55-.65	(.77-.88)	.43-.58	.64-.80	(.88-1.0)	.58-.83	(.80-1.1)	(1.0-1.3)
	300	.21-.29	.30-.39	.40-.50	.28-.41	.38-.52	.48-.63	.40-.65	.51-.76	.62-.88
	600	.14-.22	.19-.27	.23-.32	.20-.33	.25-.38	.30-.44	.32-.56	.37-.61	.42-.67
30	20	(2.9-3.2)	[5.6-6.0]		(3.2-3.8)	(6.0-6.6)		(3.8-4.6)	(6.7-7.6)	
	40	1.5-1.8	(2.7-3.0)	[4.0-4.3]	(1.8-2.2)	(3.0-3.4)	(4.3-4.8)	(2.2-2.9)	(3.5-4.2)	(4.8-5.6)
	80	.82-1.0	1.4-1.6	(2.0-2.2)	1.0-1.4	1.6-2.0	(2.2-2.6)	1.4-2.0	(2.0-2.6)	(2.6-3.2)
	150	.51-.71	.78-.99	1.1-1.3	.68-.99	.96-1.3	1.3-1.6	.97-1.5	1.3-1.8	(1.6-2.2)
	300	.34-.53	.47-.66	.59-.80	.48-.77	.61-.91	.74-1.1	.74-1.3	.88-1.4	1.0-1.6
	600	.26-.44	.32-.50	.38-.57	.38-.67	.44-.74	.50-.81	.62-1.2	.69-1.2	.76-1.3
40	20	(3.6-4 1)	[6.7-7.3]	[10-11]	(4.1-4.9)	(7.4-8.2)	(11-12)	(5.0-6.3)	(8.3-9.7)	(12-13)
	40	1.9-2.3	(3.3-3.8)	(4.8-5.3)	2.3-3.0	(3.8-4.5)	(5.3-6.1)	(3.0-4.1)	(4.5-5.6)	(6.1-7.3)
	80	1.1-1.5	1.7-2.1	2.4-2.8	1.4-2.0	2.1-2.7	2.8-3.4	2.0-3.0	2.7-3.7	(3.4-4.5)
	150	.72-1.1	1.0-1.4	1.4-1.8	.98-1.5	1.3-1.9	1.7-2.2	1.5-2.4	1.8-2.8	2.2-3.2
	300	.51-.84	.66-1.0	.81-1.2	.74-1.3	.89-1.4	1.1-1.6	1.2-2.2	1.4-2.3	1.5-2.5
	600	.41-.74	.48-.81	.55-.89	.61-1.1	.69-1.2	.77-1.3	1.1-2.0	1.1-2.1	1.2-2.2
60	20	4.9-5.9	(8.9-10)	(13-14)	5.9-7.4	(10-12)	(14-16)	(7.5-10)	(12-14)	(16-19)
	40	2.8-3.6	4.6-5.5	6.5-7.4	3.5-4.8	5.4-6.7	(7.3-8.8)	4.8-7.0	(6.7-9.1)	(8.7-11)
	80	1.7-2.5	2.5-3.4	3.4-4.3	2.3-3.5	3.2-4.4	4.1-5.4	3.4-5.6	4.3-6.6	5.2-7.6
	150	1.2-2.0	1.6-2.4	2.1-2.9	1.7-2.9	2.2-3.4	2.6-3.9	2.8-4.9	3.2-5.4	3.7-5.9
	300	.95-1.7	1.2-1.9	1.3-2.1	1.4-2.6	1.6-2.8	1.8-3.1	2.4-4.6	2.6-4.8	2.9-5.1
	600	.82-1.6	.92-1.7	1.0-1.8	1.3-2.4	1.4-2.6	1.5-2.7	2.2-4.4	2.3-4.5	2.5-4.6

For SI Units: 1 ft = .3048 m; 1 ft² = .0929 m².

Notes to Table 4-3

1. Vents are assumed to be spaced at one-half of the curtain board spacing. (*See 4-3.1.9 and 4-3.4 for other spacings.*)
2. Curtain depth assumed at 20 percent of ceiling height. (*See 4-3.1.9 for other depths.*)
3. Each entry is the vent-area range (in 1000 ft²) associated with heat-responsive devices rated between 100°F and 220°F (37.8°C and 104.4°C) above ambient temperature.
4. No Entries: Heat-release rates greater than $Q_{feasible}$.
5. Entries Boxed-In: Not possible, but needed for curtain depths greater than 20 percent.
6. Entries in Parentheses: Correspond to levels of heat release greater than Q_{1000}.

4-3.2.2 For curtain depths greater than 20 percent of the ceiling height, the calculated vent area, A_{1000}, associated with heat-release rate Q_{1000}, can be calculated from the following equation (where H is the ceiling height in ft and d is the curtain depth in ft):

$$A_{1000}\,(ft^2) = \frac{1.6\,(H-d)^{5/2}}{d^{1/2}}$$

4-3.2.3 For curtain depths greater than 20 percent of the ceiling height, the calculated vent area, $A_{feasible}$, associated with $Q_{feasible}$, can be estimated from:

$$A_{feasible}\,(ft^2) = \frac{8.5\,(H-d)^{5/2}}{d^{1/2}}$$

4-3.3 Vent areas per curtained compartment, determined according to 4-3.1.2 and 4-3.1.9 or 4-3.1.2, should be sized and distributed within the constraints of 2-4.1. In some cases, the calculated number of vents may be so large that the vent spacing will be considerably smaller than the design spacing for vents assumed in Table 4-3, ½ S_c. The closer vent spacing implies earlier operation of the first vents than is the case for the designs of Table 4-3. Earlier operation, like an auxiliary fire detection system, would, under conditions of clear visibility, increase the time available for carrying out activities of the types outlined in 1-1.3.

4-3.4 The extra time identified in 4-3.3 is represented by the symbol Δt_e and can be estimated from the equation:

$$\Delta t_e\,(min) = C \times [t_g\,(sec)]^{0.9} \times [H(ft)]^{1\,2}$$

4-3.4.1 Here, t_g is the growth time and H is the ceiling height. The coefficient C depends on the curtain board spacing (S_c), vent spacing (S_v), as well as the temperature rating of the heat-responsive devices. For devices rated at 100°F (37.8°C) above the ambient temperature, some values of C are:

$S_c = 8 \times H$, $S_v = \frac{1}{2} S_c$: C = 0 (design case, Table 4-3)
$S_c = 8 \times H$, $S_v = \frac{1}{4} S_c$: C = 0.0010
$S_c = 8 \times H$, $S_v = \frac{1}{8} S_c$: C = 0.0016
$S_c = 4 \times H$, $S_v = \frac{1}{2} S_c$: C = 0 (design case, Table 4-3)
$S_c = 4 \times H$, $S_v = \frac{1}{4} S_c$: C = 0.0005

4-3.4.2 For heat-responsive devices rated at 220°F (104.4°C), the values of C above are to be increased by about 60 percent.

4-3.4.3 The extra time is not very significant for fast-growing fires. However, for slow-growing fires, the extra time may be significant. [For t_g = 600 seconds, $S_c = 8 \times H$ and $S_v = \frac{1}{4} S_c$, the extra time varies from 8-13 minutes at 15-ft (4.57-m) ceiling height to 40-70 minutes at 60-ft (18.3-m) ceiling height.]

4-3.4.4 The extra time available with vents spaced at less than ½ S_c may be considered to represent a safety factor for venting systems designed according to 4-3.1.2 and 4-3.1.9.

4-3.5 Consult Table 4-2 for examples on growth time. Most of the examples pertain to fairly high storage. Estimates for lower heights may be made by noting the relative effect of storage height on growth time for wood pallets. Careful engineering judgment is needed in interpreting Table 4-2 and for assessing other material arrays.

4-4 Fresh Air Make-Up.

4-4.1 To function as intended, a venting system needs sufficiently large fresh air openings at low levels in the building. In order to be effective, the total area of these openings must normally be at least as great as the installed vent area per curtained compartment.

4-4.2 If doors and windows below designed smoke level cannot meet the total required inlet area, special air-inlet provisions are necessary.

4-4.3 It is essential that a dependable means for providing inlet air within one minute after the first vent opens be provided.

Chapter 5 Inspection and Maintenance

5-1 Importance. Vents, like other fire protection equipment, are vulnerable to mishandling, improper installation and on-site impairments. This is especially true for emergency equipment that may not be subject to fire use for many years. Thus, regular inspection and maintenance are essential.

5-2 General.

5-2.1 Various types of approved automatic thermal smoke and heat vents have been made available commercially that fall into two general categories:

5-2.1.1 Mechanically Opened Vents. (For example: spring-lift, pneumatic-lift or electric motor-driven.)

5-2.1.2 Gravity-Opened Vents. (For example: PVC or acrylic drop-out panels.)

5-2.2 Generally, mechanically opened vents are provided with manual release devices that permit direct inspection and/or maintenance as well as replacement of actuation components (heat-responsive devices, thermal sensors, compressed gas cylinders, explosive squibs, etc.).

5-2.3 Gravity-opened vents do not permit nondestructive operation, but inspection of the installed unit is necessary to ensure the units were installed in accordance with accepted trade practices and all components are in place, undamaged and free of soiling, debris and extraneous items that may interfere with the function of the unit.

5-2.4 The inspection and maintenance of multiple-function vents need to assure that other functions will not impair the intended fire protection operation.

5-3 Frequency of Inspection and Maintenance.

5-3.1 Mechanically Opened Vents.

5-3.1.1 The manufacturer's recommendations regarding maintenance and inspection schedule of mechanically operated vents are necessary.

5-3.1.2 It is important that an acceptance performance test and inspection of all mechanically opened vents be conducted immediately following installation to establish that all operating mechanisms function properly and that the installation is in accordance with accepted trade practices.

5-3.1.3 Written schedules and procedures for inspection and maintenance need to include provisions for all units to be tested at 12-month intervals or a scheduling of percentage of the total units to be tested each month or each two months. Such procedures improve reliability.

5-3.1.4 Recording of all pertinent characteristics of performance and logging to permit comparison of results with those of previous inspection or acceptance tests will permit a comparison which provides a basis for determining need for maintenance or for modifying the frequency of the inspection schedule to fit the experience.

5-3.1.5 Where there is a change in plant occupancy, or in neighboring plants, which might introduce a significant change in nature or severity of corrosive atmosphere exposure, debris accumulation, or physical encumbrance, a change in the inspection schedule may be needed.

5-3.1.6 Special mechanisms such as gas cylinders, thermal sensors, or detectors need to be checked regularly on a schedule provided by the manufacturer.

5-3.2 Gravity-Opened Vents.

5-3.2.1 The same general considerations for inspection that apply to mechanically opened vents (*see 5-3.1*) also pertain to gravity-opened vents. The thermoplastic panels of these vents are designed to soften and "drop-out" into the vent opening in response to the heat of a fire. This mode of behavior makes impractical an operational test after installation. Recognized fire protection testing laboratories have developed standards and procedures for evaluating gravity-opened vents including factory and field inspection schedules.

5-3.2.2 An acceptance inspection of all gravity-opened vents should be conducted immediately after installation. Manufacturers' drawings and recommendations should be verified by direct examination. A suitable installation should follow accepted trade practices.

5-3.2.3 A written schedule and procedures for inspection and maintenance need to be enforced and also provide for written notations as to time, date, changes in appearance, damage to any component, fastening security, weathertightness, adjacent roof and flashing condition.

5-3.2.4 Prompt and careful removal of any soiling, debris or encumbrances which could impair the operation of the vent is essential.

5-4 Conduct and Observation of Operational Tests.

5-4.1 Mechanically Opened Vents.

5-4.1.1 Where feasible, release of the vent should simulate actual fire conditions by disconnecting the restraining cable at the heat-responsive device (or other releasing device) and suddenly releasing the restraint, thus permitting the trigger or latching mechanism to operate normally.

5-4.1.2 Since the heat-responsive device restraining cable is usually under considerable tension, observation of its whip and travel to determine any possibility that the vent, building construction feature, or service piping, which could obstruct complete release, is desirable. Any possible interference needs to be corrected by removal of obstruction, enclosure of cable in a suitable conduit, or other appropriate rearrangement. Following any modification, the unit needs to be retested for evaluation of adequacy of corrective measures.

NOTE: The whipping action of the cable upon release presents the possibility of injury to anyone in the area. For this reason, the person conducting the test must ensure that he/she and all other personnel are well clear of the area where whipping of the cable may occur.

5-4.1.3 The latch needs to release smoothly, and the vent to start to open immediately, and move through its design travel to full-open position without any prompting and without undue delay indicative of sticking weather seal, corroded or unaligned bearings, or distortion binding, etc.

5-4.1.4 Manual releases need to be tested to determine that the vents will operate.

5-4.1.5 All operating levers, latches, hinges, and weather-sealed surfaces should be examined to determine any indication of deterioration, accumulation of foreign material, etc., which might warrant corrective action or suggest another inspection in advance of the normal schedule.

5-4.1.6 Following painting of the interior or exterior of vents, the units need to be opened and inspected as a check against the gluing characteristic of paint between matching surfaces. Painted heat-responsive devices need to be replaced with devices having an equivalent temperature and load rating.

5-4.2 Gravity-Opened Vents.

5-4.2.1 Testing of manual releases is considered a part of total testing to assure that the vents will operate.

5-4.2.2 Following painting of the interior or exterior of vents, it is important to open and inspect them as a check against the gluing characteristic of paint between matching surfaces.

5-5 Ice and Snow Removal. Removal of ice and snow from vents is an essential part of a maintenance program for such devices.

Chapter 6 Venting in Sprinklered Buildings

6-1 Two popular elements of hazard control have been developed over the years, namely, sprinklers and vents. Each was developed independent of the other. The previous sections represent the state of technology of vent design in the absence of sprinklers. An equivalent, generalized design basis for using both sprinklers and vents together for hazard control (e.g., property protection, life safety, water usage, obscuration, etc.) has not been developed and is not presently available.

6-2 Concern has been raised that inclusion of automatic roof venting may be detrimental to the performance of automatic sprinklers. Although there is no universally accepted conclusion from fire experience [Section 6-5(a)], studies on a model scale [Section 6-5(b)] suggested:

(a) Venting delays loss of visibility.

(b) Venting results in increased fuel consumption.

(c) Depending on the location of the fire relative to the vents, the necessary water demand to achieve control is either increased or decreased over an unvented condition. With the fire directly under the vent, water demand is decreased. With the fire equidistant from the vents, water demand is increased.

6-3 A series of tests was conducted to increase the understanding of the role of automatic roof vents simultaneously employed with automatic sprinklers [Section 6-5(c)]. The data submitted did not permit consensus to be developed whether sprinkler control was impaired or enhanced by the presence of automatic (roof) vents of typical spacing and area.

6-4 While the use of automatic venting in sprinklered buildings is still under review, the designer is encouraged to use the available tools and data referenced in this document for solving problems peculiar to a particular type of hazard control.

6-5 References of interest include:

(a) Miller, E. E., Position Paper to 204 Subcommittee, "Fire Venting of Sprinklered Property."

(b) Heskestad, G., *Model Study of Automatic Smoke and Heat Vent Performance in Sprinklered Fires*, Technical Report FMRC Serial No. 21933RC74-T-29, Factory Mutual Research Corp., MA, September 1974.

(c) Waterman, T. E., et al., *Fire Venting of Sprinklered Buildings*, IITRI Project J08385 for Fire Venting Research Committee, IIT Research Institute, Chicago, IL 60616, July 1982.

Appendix A Derivation of Venting Relationships

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

A-1 At the time this guide was formulated, an approximate venting theory already existed (*see Section A-9, references 1 and 2*) which has served as a foundation of several European venting standards. However, that theory was deemed unwieldy for the format of this venting guide. Consequently, the alternative, more adaptable theory described here was adopted. It is emphasized that the alternative theory gives results for specific venting situations which do not differ greatly from the predictions of the previous theory.

Elements of Problem.

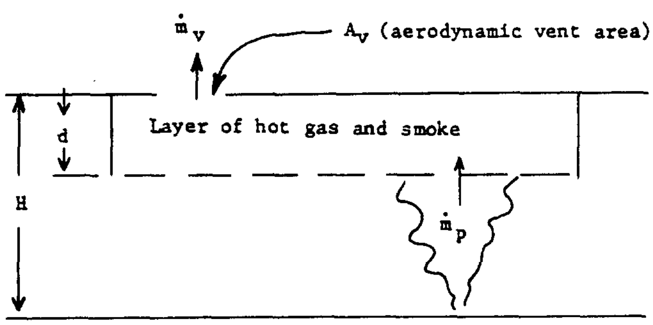


Figure A-1 Schematic of Venting System.

A-2 Refer to Figure A-1. Assume steady state. H is the floor-to-ceiling height; d is the depth of the curtain boards (or design depth of the smoke layer); $\dot{m}_p$ is the mass flow rate of hot gases from the fire plume into the smoke layer; $\dot{m}_v$ is the mass flow rate of hot gas out of the vent (or vents); and A_v is the aerodynamic vent area (total aerodynamic vent area in curtained compartment, if several vents). At equilibrium, the mass flow rate into the smoke layer ($\dot{m}_p$) matches exactly the mass flow rate out of the vent ($\dot{m}_v$). In the following, separate sections are devoted to obtaining mathematical expressions for $\dot{m}_p$ and $\dot{m}_v$ which, subsequently, are matched to yield expressions for the required vent area, A_v.

A-3 Mass Flow Rate in Plume, $\dot{m}_p$.

At a given elevation within the plume, below the level where the plume enters the smoke layer, the local mass flow rate in the plume is:

$$\dot{m}_p = \int_0^R u\varrho 2\pi r dr \qquad (1)$$

where u is the gas velocity; ϱ is the mass density of the gas; r is the observation radius; and R is the radius of the fire plume. The gas density, ϱ, can be written:

$$\varrho = \varrho_0 - \Delta\varrho \qquad (2)$$

where ϱ_0 is the ambient density and $\Delta\varrho$ is the local density defect relative to the ambient density. The following relation can be formed from equations (1) and (2):

$$\dot{m}_p = 2\pi R^2 u_c \left[\varrho_0 \int_0^1 \frac{u}{u_c} \frac{r}{R} d\left(\frac{r}{R}\right) - \Delta\varrho_c \int_0^1 \frac{u}{u_c} \frac{\Delta\varrho}{\Delta\varrho_c} \frac{r}{R} d\left(\frac{r}{R}\right) \right] \qquad (3)$$

where u_c and $\Delta\varrho_c$ are centerline values of u and $\Delta\varrho$, respectively.

It is now assumed that the flow in the plume is self-preserving; i.e., profiles of velocity and density defect preserve their shapes along the plume axis except for changes in centerline values and changes in the plume radius. Under this assumption, the integrals in equation (3) are universal, nondimensional constants. Then equation (3) can be written:

$$\dot{m}_p = 2\pi R^2 u_c \left[A\varrho_0 - B\,\Delta\varrho_c \right] \qquad (4)$$

where:

$$A = \int_0^1 \frac{u}{u_c} \frac{r}{R} d\left[\frac{r}{R}\right] \qquad (5)$$

$$B = \int_0^1 \frac{u}{u_c} \frac{\Delta\varrho}{\Delta\varrho_c} \frac{r}{R} d\left[\frac{r}{R}\right] \qquad (6)$$

To develop equation (4) further, an expression for the flux of convective heat in the plume is sought. First, note that the flux of convective heat, Q, can be considered conserved along the plume axis and can be written:

$$Q = C_p \int_0^R \varrho u \,\Delta T\, 2\pi r dr \qquad (7)$$

where C_p is the specific heat of the plume gases (essentially air) and ΔT is the local excess temperature of the plume gases relative to the ambient temperature. With the aid of the equation of state for a perfect gas, it can be shown:

$$\varrho u \Delta T = u\, T_0\, \Delta\varrho \qquad (8)$$

where T_0 is the ambient temperature. With equation (8), equation (7) can be written:

$$Q = 2\pi R^2 C_p\, T_0\, u_c\, \Delta\varrho_c \int_0^1 \frac{u}{u_c} \frac{\Delta\varrho}{\Delta\varrho_c} \frac{r}{R}\, d\left[\frac{r}{R}\right] \qquad (9)$$

or using the definition in equation (6):

$$Q = 2\pi R^2 C_p\, T_0\, u_c\, \Delta\varrho_c\, B \qquad (10)$$

Substitution for $2\pi R^2 u_c$ from equation (10) into equation (4) gives:

$$\dot{m}_p = \frac{Q\left[1 - \frac{B}{A}\frac{\Delta\varrho_c}{\varrho_0}\right]}{C_p\, T_0\, (B/A)\, (\Delta\varrho_c/\varrho_0)} \qquad (11)$$

With the aid of the equation of state for a perfect gas, equation (11) can be written:

$$\dot{m}_p = \frac{Q\left[1 + \left(1 - \frac{B}{A}\right)\frac{\Delta T_c}{T_0}\right]}{C_p\, (B/A)\, \Delta T_c} \qquad (12)$$

Measurements of plume profiles (3) have given values $A = 0.164$ and $B = 0.111$, such that $B/A = 0.68$. For plume centerline temperatures, the following relation is consistent with theory and experiments (4):

$$\Delta T_c/T_0 = 0.60\, Q^{2/3} z^{-5/3} \qquad (13)$$

where z is, approximately, the elevation above the fire source (Q in Btu/second, z in ft). With the aid of these results, equation (12) takes the following engineering form:

$$\dot{m}_p\,(\text{lb/s}) = C\, Q^{1/3} z^{5/3} [1 + 0.19\, Q^{2/3} z^{-5/3}] \qquad (14)$$

where $C = 0.019$. A direct measurement of mass flow rate in a fire plume (3) has indicated that a better value for C is:

$$C = 0.022 \qquad (15)$$

In the vent problem, the elevation in the plume at entry into the smoke layer is $z = H-d$, assuming the fire source does not reach much above the floor level. Hence, the mass flow rate feeding the smoke layer is, from equations (14) and (15):

$$\dot{m}_p\,(\text{lb/s}) = 0.022\, Q^{1/3} (H-d)^{5/3} [1 + 0.19\, Q^{2/3} (H-d)^{-5/3}] \qquad (16)$$

Equation (16) ceases to be valid when the continuous flaming region (as opposed to the intermittent flaming region) reaches into the smoke layer, which essentially coincides with the occurrence of a gas temperature rise of about 1600°F (871.1°C) ("flame temperature") in the plume as it enters the smoke layer. According to equation (13), the associated (convective) heat-release rate, $Q = Q_c$, is calculated as:

$$Q_c\,(\text{Btu/sec}) = 11.3\, (H-d)^{5/2} \qquad (17)$$

At heat-release rates greater than Q_c, the mass flow rate into the smoke layer from the fire is estimated from the entrainment relation by Ricou and Spaulding[5]. This relation is:

$$\frac{d\dot{m}_p}{dz} = K\, (M\varrho_0)^{1/2} \qquad (18)$$

where K is an "entrainment constant" (nondimensional) and M is the local momentum flux in the plume. Assuming that the continuous flaming region beneath the smoke layer has a constant centerline velocity, u_f; gas density, ϱ_f; and radius, b_f, the entrained flow beneath the smoke layer is estimated to be proportional to:

$$\dot{m}_p \propto (H-d)\, (M\varrho_0)^{1/2} \propto (H-d)\, (\varrho_f u_f^2\, b_f^2\, \varrho_0)^{1/2} \qquad (19)$$

An expression for the radius of the fire plume, b_f, follows from the expression for convective heat flux:

$$Q \propto \varrho_f\, u_f\, b_f^2\, C_p\, \Delta T_f \qquad (20)$$

Substitution for b_f in equation (19) from equation (20) results in the following proportionality if ϱ_0, C_p and ΔT_f are considered constant:

$$\dot{m}_p \propto (H-d)\, u_f^{1/2}\, Q^{1/2} \qquad (21)$$

For the flame-gas velocities, u_f, it is known from past work[6] that:

$$u_f \propto Q^{1/5} \qquad (22)$$

which in equation (21) gives:

$$\dot{m}_p \propto (H-d)\, Q^{3/5} \qquad (23)$$

Hence, knowing the mass flow rate into the smoke layer for a heat-release rate of Q_c [from equation (16), with $Q = Q_c$ according to equation (17)], mass flow rates at greater heat-release rates follow from:

$$\dot{m}_p = (\dot{m}_p)_c\, (Q/Q_c)^{3/5} \qquad (24)$$

where $(\dot{m}_p)_c$ is $\dot{m}_p$ at $Q = Q_c$.

Note that for $Q = Q_c$, the convective heat flux, Q, must be regarded as a pseudo heat flux, being the convective heat flux of the associated "free-burning" fire, which is not influenced by the vitiated air of the smoke layer. Unreacted fuel carried by the plume into the smoke layer will not burn to completion, and the actual heat released will be less than in free-burn. To avoid ambiguity, the convective heat flux Q should always be interpreted, in this theory, as the convective heat produced by the associated free-burning fire at the mass burning rate of the actual building fire.

A-4 Mass Flow Rate Through Vents, $\dot{m}_v$.

Assume first that the entry area for fresh air into the building is "not small" (at least as large as vent area according to Thomas and Hinkley[2]).

Equating the buoyancy head across the vent to the dynamic head in the vent (from Bernoulli's equation) gives:

$$\tfrac{1}{2}\,\varrho u^2 = \Delta\varrho g\, d \qquad (25)$$

where ϱ is the smoke layer density, $\Delta\varrho = \varrho_0 - \varrho$, u is the gas velocity in the vent, and g is the acceleration of gravity. It follows from equation (25) that:

$$\dot{m}_v{}^2 = A_v{}^2\, \varrho^2\, u^2 = 2A_v{}^2\, \varrho\Delta\varrho\, g\, d \qquad (26)$$

where A_v is the aerodynamic vent area (well approximated by 0.6 times geometric through-flow area for simple apertures). From the equation of state for a perfect gas:

$$\varrho\Delta\varrho = \varrho_0{}^2\,\frac{T_0\,\Delta T}{T^2} \qquad (27)$$

where T is the smoke layer temperature and $\Delta T = T - T_0$. Then equation (26) becomes:

$$\dot{m}_v = (2\,\varrho_0{}^2\, g)^{1/2}\left[\frac{T_0\,\Delta T}{T^2}\right]^{1/2} A_v d^{1/2} \qquad (28)$$

Note that the factor $(T_0\,\Delta T/T^2)^{1/2}$ is quite insensitive to temperature as long as the smoke layer temperature is not small. For example, assuming T_0 = 530 R, the factor varies through 0.47, 0.50, 0.48 as the smoke layer temperature varies through 350°F (176.7°C), 600°F (315.5°C), 1000°F (537.7°C). Consequently, it is simply assumed in the vent application that the factor may be taken as constant at:

$$\left[\frac{T_0\,\Delta T}{T^2}\right]^{1/2} = 0.5 \qquad (29)$$

A-5 Required Vent Area Versus Heat-Release Rate.

The mass flow rate through the vent, equation (28) with the approximation in equation (29), is equated with the mass flow rate into the smoke layer:

$$0.5\,(2\,\varrho_0{}^2\, g)^{1/2}\, A_v d^{1/2} = \dot{m}_p \qquad (30)$$

which is solved for A_v:

$$A_v = \frac{2}{(2\varrho_0{}^2\, g)^{1/2}}\,\frac{\dot{m}_p}{d^{1/2}} \qquad (31)$$

The value of $\dot{m}_p$ is determined as described in the preceding section. First Q_c is determined from equation (17) to establish which regime the fire is in. For ($Q \leq Q_c$), equation (16) for $\dot{m}_p$ is substituted into equation (31):

$$A_v\,(ft^2) = 0.073\, Q^{1/3}\,[1 + 0.19\, Q^{2/3}\,(H-d)^{-5/3}]\,\frac{(H-d)^{5/3}}{d^{1/2}} \qquad (32)$$

(Q in Btu/sec; H and d in ft)

For ($Q > Q_c$), m_p is obtained from equation (24), where $(\dot{m}_p)_c$ is calculated from equation (16) with $Q = Q_c$ according to equation (17):

$$(\dot{m}_p)_c = 0.097\,(H-d)^{5/2} \qquad (33)$$

such that:

$$\dot{m}_p = 0.097\,(H-d)^{5/2}\,(Q/Q_c)^{3/5} \qquad (34)$$

This expression for $\dot{m}_p$ is substituted into equation (31), with the desired results:

$$A_v\,(ft^2) = 0.32\,(Q/Q_c)^{3/5}\,\frac{(H-d)^{5/2}}{d^{1/2}} \qquad (35)$$

(H and d in ft)

These relations can be greatly simplified whenever Q/Q_c is larger than approximately 0.2 (nearly always the case in vent design). Then it may be shown that equations (32) and (35) can be consolidated into a single relation with the aid of equation (17), valid for heat-release rates both smaller and larger than Q_c:

$$A_v\,(ft^2) = 0.075\, Q^{3/5}\,\frac{H-d}{d^{1/2}} \qquad (36)$$

(Q in Btu/sec; H and d in ft)

A-6 Vent Areas for Steady Fires (Limited-Growth Fires).

For stationary fires, or fires that do not develop beyond a maximum size, the required vent areas are calculated from equation (32) or equation (35), depending on the heat-release rate relative to Q_c, or from the simplified expression in equation (36). Paragraphs 4-2.1.1 and 4-2.1.4 are based on the simplified relation in equation (36), with the vent areas adjusted to a discharge coefficient of 0.6.

A-7 Vent Areas for Growing Fires (Continuous-Growth Fires).

A simple fire-growth model is first stipulated:

$$Q = 1000\,(t/t_g)^2 \qquad (37)$$

(Q in Btu/sec; t and t_g in seconds)

where t is time from a virtual ignition event representative of the developed fire following an incubation period, and t_g is the time, t, at which the developed fire exceeds an intermediate size of 1000 Btu/second. The growth time, t_g, is a measure of the fire-growth rate; the smaller the growth time, the faster the fire grows.

A venting system must be able to handle the fire from the time of ignition to the last instant of the clear-visibility design time interval, t_r, as measured from the time, t_d, when the first vents activate. In other words, a venting system must be able to handle the fire at the intervention time, $t_r + t_d$, following ignition. Once the intervention time is known, the fire size at intervention can be calculated from equation (37) for the expected fire-growth time, t_g. Required vent areas are calculated from equations (32) and (35), or from the simplified expression in equation (36).

A convenient relation for the required vent area is obtained if the simplified expression in equation (36) is adopted. Together with equation (37) and the definitions of t_d and t_r, equation (36) leads to:

$$A_v(ft^2) = 4.8 \left(\frac{t_d + t_r}{t_g}\right)^{6/5} \frac{H-d}{d^{1/2}} \qquad (38)$$

(t_d, t_r, t_g in seconds; H and d in ft)

Paragraphs 4-3.1.2 and 4-3.1.9 are based on equation (38), with the vent areas adjusted to a discharge coefficient of 0.6. The detection time, t_d, was taken as the time of operation of the first vent in a square matrix (vent farthest possible from the fire location). The vents were assumed to be activated by heat-responsive devices of various temperature ratings above the ambient temperature. Link activation times (t_d) were calculated from a thermal-response equation for heat-responsive devices derived previously [7], together with generalized data on gas temperatures and velocities under extensive flat ceilings [4]. The time constant [7] of the heat-responsive device was taken as 233 seconds at 5 ft/seconds (1.53 m) gas velocity, which is considered to be a conservatively high value for heat-responsive devices listed by testing laboratories.

A-8 On Conservatism Built into Guide.

All calculations have assumed that the top of the combustible is essentially level with the building floor, which results in larger required vent areas than would higher elevations of the combustible. The underlying rationale is that by the last moments of the intervention time, and during the clear-visibility design time, the fire will be at such an advanced stage that the combustible may, in fact, have collapsed to near floor level.

For the vent activation times (t_d) needed in calculations of vent areas recommended in 4-3.1.1 and 4-3.1.9, it is recalled that an additional assumption was made, i.e., the heat-responsive device was exposed to gas temperatures and velocities similar to those generated by fires under extensive flat ceilings. This assumption may appear to be optimistic for installations involving beamed ceilings. However, any delay in vent operation due to beams is probably compensated by opposite effects of (1) heat banking up under the ceiling because of curtain boards or walls, (2) the top of the combustible being closer to the ceiling than assumed in the calculations (floor level assumed), and (3) the nearest vent to the fire usually being closer than assumed in the calculations (greatest possible distance assumed).

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Appendix B Bibliography

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

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B-2 Additional References. See Appendix A, Section A-9.