#10521

Comparison of "Regular" and "Irregular" Methods of Calculating Smoke Layer Interface Heights in 1996 BOCA National Building Code

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ABSTRACT

Although building codes have addressed the subject of smoke management in atrium spaces since the early 1980s, system performance was not described in terms of a design objective that related the development of hazardous conditions to specific fire scenarios and smoke production. Until the publication of NFPA 92B (NFPA 1991), designers were likely to use a mass flow-based calculation method to predict the position of a smoke layer interface in a large-volume space. NFPA 92B added a predictive correlation that generated a smoke layer interface position at any given time. The 1993 Building Officials and Code Administrators International (BOCA) Building Code codified the NFPA 92B approach but incorporated both predictive methods. This paper compares the two methods for a range of atrium areas and aspect ratios. The results illustrate that the two methods are not equivalent and will not produce comparable results. Further analysis was then conducted to reconcile the two methods and develop an approach that will permit designers to produce comparable hazard analyses regardless of the method used. Use of a plume centerline temperature correlation to adjust the maximum expected layer temperature is suggested as a reconciliation technique. A result of the analysis is the recommendation to reevaluate the fundamental correlation used as the basis for the regular ceiling calculation method, in order to bring it into agreement with the mass flow/entrainment used in the irregular ceiling calculation method. A suggested series of adjustments is provided to align the regular ceiling and irregular ceiling calculation method results over a broad range of interface heights.

INTRODUCTION

Atrium smoke management systems have been mandated by building codes since the early 1980s (BOCA 1981; NFPA 1981). Early requirements were based on the air change rate method, whereby the total volume of the enclosed space was used to determine airflow rates (BOCA 1981, Section 631.0). Fire size and the risks posed by the position of a smoke layer interface may have been considered in the development of the requirements, but these considerations are not documented in these earlier editions.

Prior to 1980, ongoing research and development activities were under way to develop a more performance-oriented approach that would be based on the hazards and geometry of the particular space. A summary of these activities has been presented by Klote (1994a).

Concurrently with the ASHRAE work, the National Fire Protection Association (NFPA) established the Technical Committee on Smoke Management Systems in 1985. Its first committee project became NFPA 92A, *Recommended Practice for Smoke Control Systems*, which was published in 1988.

The second project was the development of NFPA 92B, *Guide for Smoke Management Systems in Malls, Atria, and Large Areas*, first published in 1991. Whereas NFPA 92A is noted for its pressurization approach for preventing the migration of smoke from one space to another, NFPA 92B became the first consensus document to contain smoke management system design guidance based on the principle that a conical smoke plume from a fire will (1) rise to the ceiling of an enclosure, (2) form a layer at the ceiling, and (3) fill the enclosure in a predictable manner. Life safety or property conservation design objectives could be based on the predictable nature of the smoke layer interface. Figure 1 depicts the development of the fire plume, the formation of the smoke layer interface, and the filling of the enclosure as a result of a heat source located in a position where the fire plume does not meet the wall of the enclosure.

The Building Officials and Code Administrators International, Inc., adopted this concept and codified the approach within Section 921, "Smoke Control Systems," of the 1993 *BOCA National Building Code* (BOCA 1993a). Two calculation methods are presented to predict the location of the smoke layer

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interface, one based on a regular, flat ceiling and one based on an irregular ceiling shape (BOCA 1993). Figure 2 illustrates several typical ceiling configurations. Note the design height of the critical smoke interface (BOCA 1993) in each case. In three cases, spaces with flat ceilings are deemed "irregular" due to the changing horizontal cross-sectional area above the critical smoke interface. The text of the Code and the accompanying commentary (BOCA 1993b) lead the reader to believe that the two calculation methods will produce equivalent results. This is further reinforced by Figure 921.2.1.1, indicating that the regular ceiling method can be utilized in the case where the building depicted has a roof with sloping sides (producing a varying cross-sectional area).

Both methods were continued into the 1996 edition of the BOCA Building Code, with the exception that a change was made to the coefficients of the irregular ceiling (Section 922.2.1.2) [1] smoke volume equation.

The purpose of this paper is to compare the two calculation methods commonly used to predict the same event—the height of a smoke layer interface at a particular time.

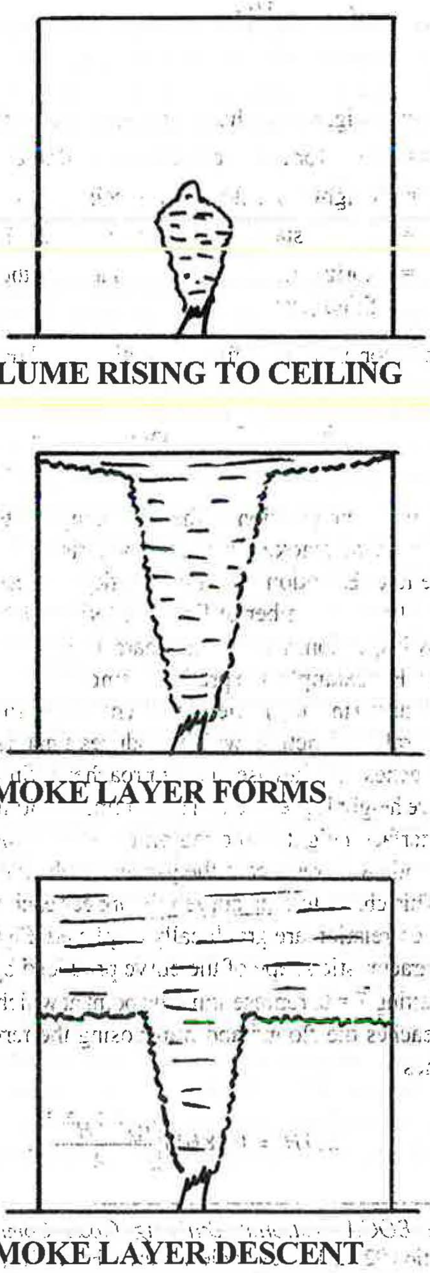

***Figure 1** Smoke filling of atrium space: (a) plume rises to ceiling; (b) smoke layer forms; (c) smoke layer descends.*

HYPOTHESIS

This paper will test the following hypothesis:

> The regular and irregular ceiling equations presented in Section 922 of the 1996 *BOCA National Building Code* will produce comparable smoke layer interface height predictions when (1) atrium A/H^2 aspect ratios are between 0.9 and 14, (2) fire sizes are limited to 2000 Btu/s (2110 kW) and 4400 Btu/s (4640 kW), (3) the ceiling of the space is flat, and (4) the space has a constant horizontal cross-sectional area.

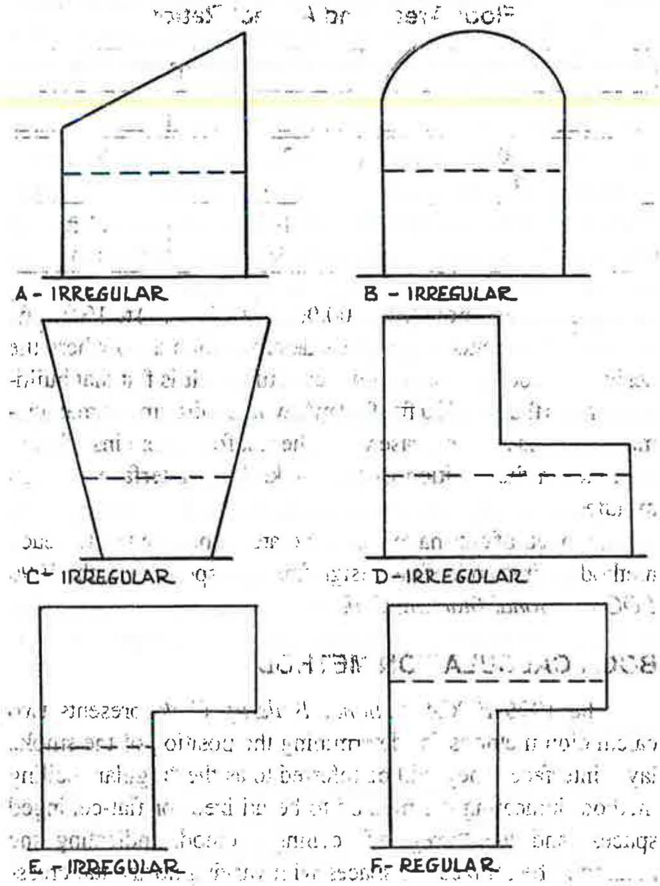

***Figure 2** Illustration of regular vs. irregular spaces. Dotted line (---) indicates design height of critical smoke interface.*

1 The *BOCA National Building Code* (1993a), Section 921, has been renumbered Section 922 in the 1996 edition.

The conditions described above represent the point of convergence of the two design methods and, therefore, represent the condition where the methods can be directly compared.

If the methods are comparable, designers will have more flexibility in choosing a calculation approach. If the methods are not comparable, there may be foreseeable conditions where the choice of calculation method may govern the need for a smoke management system and may not accurately reflect the hazard (or lack of hazard) in a particular case.

METHODOLOGY

In order to test the hypothesis that the two prediction methods will produce equivalent results over a range of conditions, two different building areas were selected. For each area selected, both calculation methods were used to predict the position of the smoke layer interface as a function of time for two different atrium aspect ratios. These areas, along with the corresponding heights for the different aspect ratios, are presented in Table 1.

TABLE 1
Ceiling Heights for Selected Floor Areas and Aspect Ratios

	A/H^2	
Area	0.9	14
100,000 ft^2 ($9290 \; m^2$)	333 ft (101 m)	84 ft (26 m)
10,000 ft^2 ($929 \; m^2$)	109 ft (33 m)	27 ft (8 m)

The range of areas from 100,000 ft^2 (9,290 m^2) to 10,000 ft^2 (929 m^2) represents the author's determination as to where the design method will be most widely utilized. It is felt that buildings of less than 10,000 ft^2 (929 m^2) will require smoke management systems in every case when the test for system installation is based on the position of the smoke layer interface after 20 minutes.

Two sets of data have been generated. The data sets test each method against both of the design fire sizes specified in the 1996 *BOCA National Building Code*.

BOCA CALCULATION METHODS

The 1996 *BOCA National Building Code* presents two calculation methods for determining the position of the smoke layer interface. They will be referred to as the "regular" ceiling method, indicating the method to be utilized for flat-ceilinged spaces, and the "irregular" ceiling method, indicating the method to be utilized for spaces with varying horizontal cross-sectional areas. Both methods can be traced to information provided in the 1991 edition of NFPA 92B.

Figure 3 illustrates a cross-sectional view of an atrium, indicating some of the terminology that will be utilized in the discussion of the calculation methods. The terms used are defined as follows:

H = highest point of smoke accumulation,
Z = height of smoke layer interface,
Z_{CR} = critical (design) height of smoke layer interface,
z_l = limiting elevation (defined as the height of the luminous flame), and
A = horizontal cross-sectional area of atrium.

Regular Ceiling Method

The position of the smoke layer interface, Z, is predicted at any time using the following equation:

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

where

Z = height from the floor to the smoke interface (ft),
t = time for the interface to extend to Z (s),
H = height from floor to flat ceiling (ft),
Q = steady-state heat release rate (Btu/s), and
A = horizontal cross-sectional area of the space being filled (ft^2).

The equation is derived from Equation 9 in NFPA 92B:

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

representing the position of the smoke layer interface based on the volume of smoke produced by a fire with a steady heat release rate. Equation 2 is a correlation representing a "curve fit" of a limited number of fire tests (NFPA 1995).

By inspection, some of the characteristics of Equation 1 are evident. For example, the predicted smoke layer interface height will equal ∞ (infinity) when $t = 0$. This is due to the presence of the natural log function, which produces a natural log of $-\infty$ as t approaches 0. Likewise, as t approaches infinity, an infinitely negative height is predicted. Thus, if time is plotted on the x-axis and interface height is plotted on the y-axis, the curve will be asymptotic with respect to the y-axis yet always intersect the x-axis. This characteristic curve will appear each time the results of this correlation are graphically displayed. Figure 4 illustrates the characteristic shape of the curve produced by Equation 1.

Setting $Z = 0$, representing the point at which the layer interface reaches the floor,[2] and transposing the terms, Equation 1 becomes

$$0.67H = 0.28H\ln\left[\frac{tQ^{1/3}H^{2/3}}{A}\right]. \quad (3)$$

2. The *BOCA National Building Code Commentary* (1993), Section 921.2.1.1 (example 1), and NFPA 92B (1991), appendix E (example 3), permit the designer to utilize Equation 1 in this manner. The same example in NFPA 92B (1995) includes a cautionary note that "smoke layer heights less than 0.2 H are *not reliably estimated. . . .*" (author's italics added).

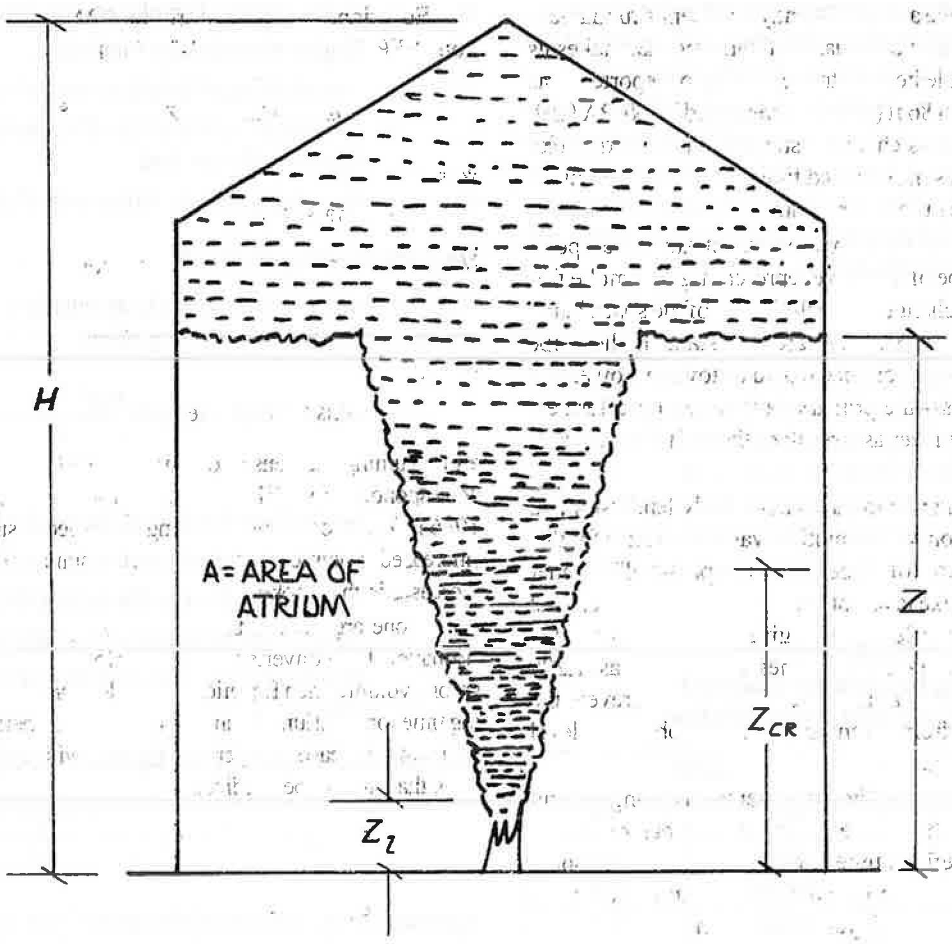

Figure 3 *Terminology: H - Highest point of smoke accumulation, Z - Height of smoke layer interface, Z_{cr} - Critical (design) height of smoke layer interface, Z_2 - Limiting elevation (height of luminous flame).*

Dividing by $0.28H$ yields:

$$2.39 = \ln\left[\frac{tQ^{1/3}H^{2/3}}{A}\right]. \quad (4)$$

This is equivalent to

$$10.94 = \frac{tQ^{1/3}H^{2/3}}{A}. \quad (5)$$

Solving for t,

$$t = 10.94A/(Q^{1/3}H^{2/3}). \quad (6)$$

Note the following characteristics with respect to Equation 6:

1. The "time to fill" varies directly with area. As the atrium area (and volume) increases, the time to fill will also increase.
2. The "time to fill" varies inversely with the heat release rate of the fire. As the fire size increases, the time to fill decreases.
3. The "time to fill" varies inversely with the height of the atrium. As the atrium height (and volume) increases, the time to fill decreases.

Observations 1 and 2 are intuitive in nature, but observation 3 is not. If area and fire size remain constant, Equation 6 can be rewritten as

$$t = C/H^{2/3}. \quad (7)$$

Using a value of $H = 1$,

$$t = C/1^{2/3}. \quad (8)$$

In this case, $t = C$.

Using a value of $H = 2$, representing a doubling of the height (and volume) of the atrium,

$$t = C/2^{2/3}. \quad (9)$$

In this case, $t = 0.63C$. Therefore, if an atrium area and fire size are held constant, the predicted filling time will decrease as the height of the atrium increases. In other words, doubling the height of a space will cause it to fill 1.59 times as fast.

In the opinion of the author, this may represent a fundamental flaw in the formulation of Equation 1, and one that makes its application questionable beyond the few series of reported tests in buildings of less than 86 ft (26.3 m) referenced by NFPA 92B. For shorter buildings, this characteristic is masked by the relatively small differences in predicted times. For taller buildings, the differences become more apparent.

The expected condition is one where, at any given point above the fire, the slope of the curve representing the smoke filling of a space will not change due to the height of the space being considered—keeping fire size and area constant. If the slope were to vary, the expected variance would be toward slower filling of the taller spaces—the primary cause due to greater heat losses from the smoke layer as a result of the additional surface area of the enclosure.

The regular ceiling method does not readily lend itself to a hand-calculated solution for t at multiple values of Z. It is for this reason that it would most often be used in a "pass-fail" manner to determine if the smoke layer interface has reached the critical height (design objective level) in a given period. (The 1996 *BOCA National Building Code* defines this period as 1,200 seconds and mandates that a smoke control system[3] prevent the smoke layer interface from reaching this design objective level in less than 1,200 seconds.)

The usefulness of this method is presented as a single-point "test" to determine if the smoke layer interface has reached a given point (Z) in a defined time period. However, with some manipulation, the use of the method can be expanded to graphically plot the position of the layer at any given time.

Irregular Ceiling Method

The volume of smoke produced at any height Z is predicted by the following equation (BOCA 1996, Section 922.2.1.2):

$$V = 17.6Q_c^{1/3}Z^{5/3} + 3.36Q_c \qquad (10)$$

where

V = volumetric rate of smoke production (ft^3/s),

Q_c = convective portion of the heat release rate (Btu/s),

where

$$Q_c = 0.7Q. \qquad (10a)$$

For a particular height, V defines a volume of smoke produced per unit of time (in this case, per minute). Smoke is assumed to be deposited on the ceiling in uniform thicknesses across the entire surface. No transit time from the fire to the ceiling, or radially from the center of plume contact to the perimeter walls, is incorporated into the equation.

3. The *BOCA National Building Code* (1996) uses the term "smoke control system" in conjunction with atrium spaces. NFPA (1988) reserves this definition for systems using pressurization to achieve design objectives. NFPA uses the term "smoke management" to include systems using pressurization or exhaust.

Equation 10 is derived from NFPA 92B's mass flow equation (NFPA 1995, Section 3-7.1.2(b)):

$$m = 0.022Q_c^{1/3}Z^{5/3} + 0.0042Q_c \qquad (11)$$

where

m = mass flow rate in plume at height Z (lb/s).

Mass flow is converted to volume flow using the relationship

$$V = 60m/\rho \qquad (12)$$

where

ρ = density of smoke (lb/ft^3)

and assuming the density of smoke to be 0.075 lb/ft^3 (1.2 kg/m^3) corresponding to 70°F (21°C). By making this assumption, the 1996 BOCA Code is not factoring in the decreasing smoke density (increased volume of the smoke) resulting from temperature increases in the smoke layer.

If one argued that the mass flow equation from NFPA 92B (Equation 11), converted to volume flow, is a reliable predictor of smoke volume, then Equation 10 would represent the "slowest" filling time for an atrium (no increase in layer temperature above ambient). Any increase in layer temperature will result in faster filling rates than would be predicted by Equation 10. What these actual

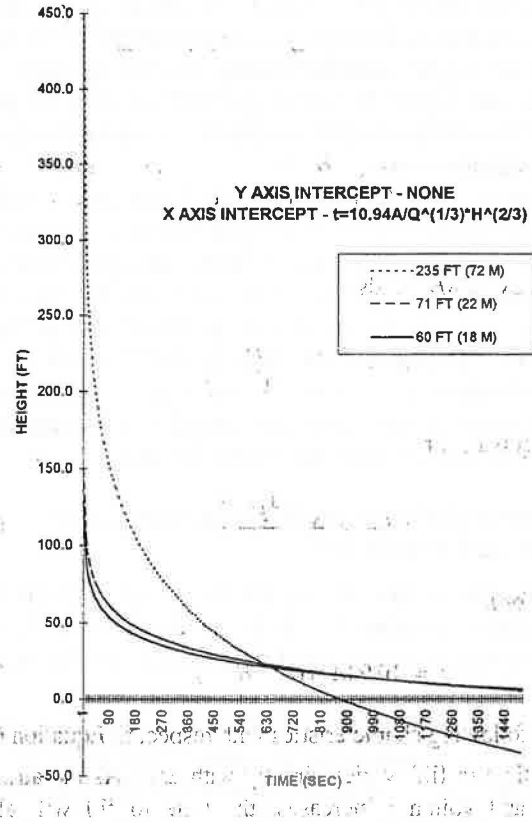

Figure 4 *Characteristic curves, regular ceiling calculation method. Area = 50,000 ft^2 (4,645 m^2); height = 235 ft (72 m), 71 ft (22 m), 60 ft (18 m); fire size = 4,400 Btu/s (4,640 kw).*

rates would be over the range of commonly designed atrium volumes is unknown due to the lack of published observations.

This method, intended for use in spaces where the horizontal cross-sectional area varies with height, is to be used in an iterative manner, as opposed to the single-point test described for the use of the regular ceiling method.

Use of Equation 10 is limited to values of Z that are above the limiting elevation. NFPA 92B and the BOCA Code are consistent in their approach here as well. The reason for this change in calculation method at this point is beyond the scope of this paper.

Below the limiting elevation height, Equation 10 is replaced by

$$V = 16.64 Q_c^{3/5} Z. \tag{13}$$

Although the limiting elevation is not defined in the 1996 BOCA Code, other references define it as the luminous flame height (NFPA 1995, Section 3-7.1.2(a)). The height is computed as

$$z_l = 0.533 Q_c^{2/5} \tag{14}$$

where

z_l = limiting elevation (luminous flame height).

Without the limiting elevation correction, Equation 10 would also predict negative values for the smoke layer interface height because of the dominance of the second term of the equation at lower heights. With the limiting elevation correction, the curve becomes asymptotic with respect to the floor of the space (x-axis). This characteristic is evident in graphical presentation of the calculation results.

Equation 13 is also based on a smoke density corresponding to a temperature of 70°F (21°C). Figure 5 illustrates the characteristic curve produced by the combination of Equations 10 and 13. Note that the curve is asymptotic with respect to the x-axis and always intersects the y-axis at H, the highest point of smoke accumulation. Inspection of Equations 10 and 13 reveals that the volume of smoke produced will be dominated by the first term for high spaces but will be more influenced by the second term as the smoke layer interface approaches the floor.

Development of Iterative Solving Approach—Regular Ceiling Method

In order to compare the predicted results produced by the two equations, a method had to be developed to display the results in a consistent way. Spreadsheets lent themselves to this task, permitting rapid iterative calculations.

A total of five columns in a spreadsheet were used for the data. The first column was filled with units of time from 1 second to 1,500 seconds, in 10-second increments. (By using 1,500 seconds, the calculations included the full 1,200-second evaluation period defined by the 1996 BOCA Code.) A 0-second point could not be calculated due to the presence of the natural log function. The next four columns were headed by the selected areas, each subdivided into separate heights for the two aspect ratios evaluated. Two sets of calculations were performed—one set for each of the mandated design fire sizes.

Equation 1 is entered for all of the times in each of the columns, and the results are a series of predicted interface heights at 10-second intervals.

Development of Iterative Solving Approach—Irregular Ceiling Method

A similar approach is used to set up the spreadsheets for the irregular ceiling method calculations. Again, the first column is used for the time intervals from 1 second to 1,500 seconds, in 10-second increments. The top cells of the next four columns contain the same height and area information as was used in the regular ceiling method calculations.

Calculating the layer position is not as straightforward as was the case for the regular ceiling method. For the irregular ceiling method, individual smoke volumes must be calculated and deposited in uniform layers at the ceiling. The layer thickness is dependent on the interval of time chosen. As each layer is added, a new Z is developed.

Starting with Equation 10, divide by 60 to convert the smoke production rate to units per second:

$$V_{sec} = 0.29 Q_c^{1/3} Z^{5/3} + 0.056 Q_c. \tag{15}$$

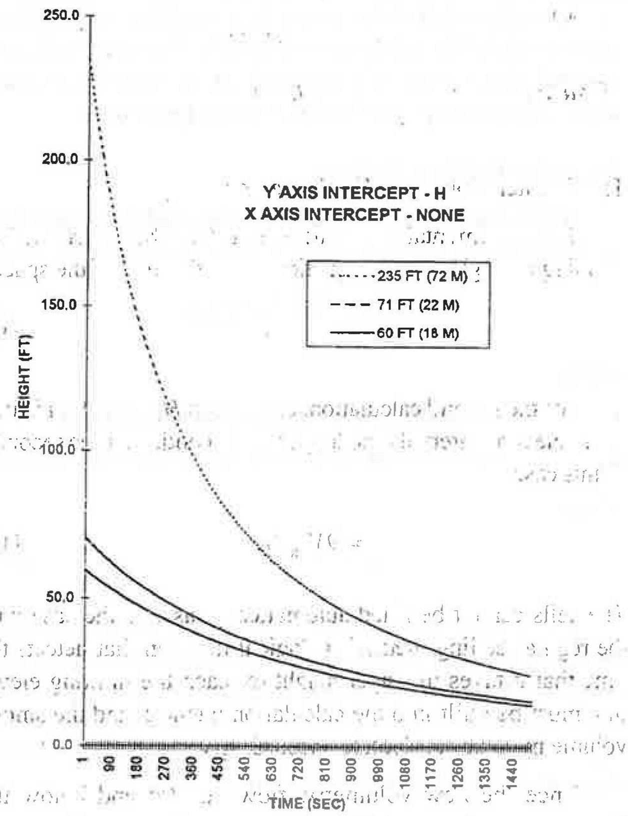

Figure 5. Characteristic curves, irregular ceiling calculation method. Area = 50,000 ft² (4,645 m²); height = 235 ft (72 m), 71 ft (22 m), 60 ft (18 m); fire size = 4,400 Btu/s (4,640 kw).

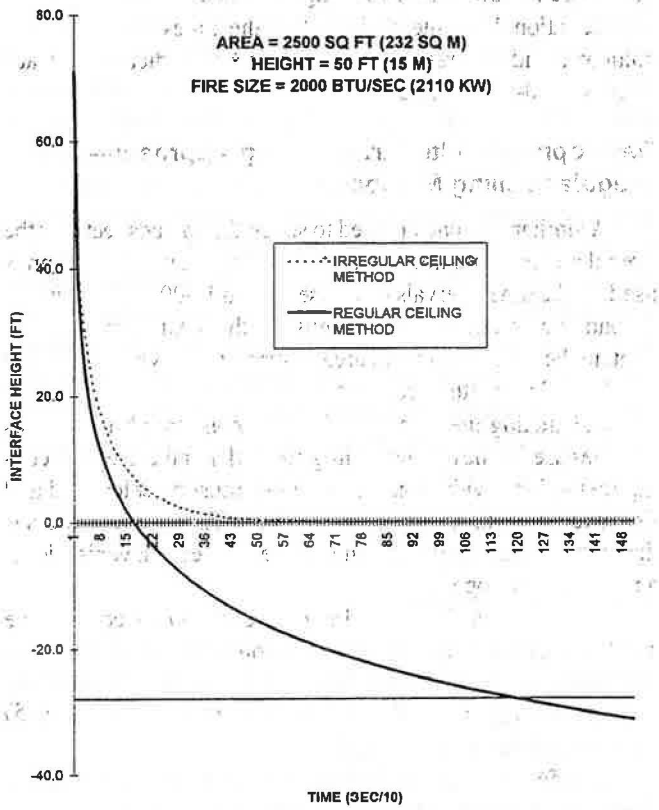

Figure 6 *Predicted smoke layer interface height using Equation 1.*

The first iteration uses H as the value for Z.

The incremental layer thickness dZ can be determined by dividing the right side of Equation 15 by the area of the space.

$$dZ = V_{sec}/A. \qquad (16)$$

For the second calculation, Z becomes $H - dZ$. In this iteration, the time interval is no longer one second, but nine seconds. In this case,

$$dZ = 9V_{sec}/A. \qquad (17)$$

The cells cannot be filled automatically, as was the case with the regular ceiling method. A logical function that detects the time that it takes the layer height to reach the limiting elevation must be built into the calculation method, and the smoke volume must be recalculated accordingly.

Once the new volumetric flow rate (at and below the limiting elevation) is incorporated into the spreadsheet, the calculation continues to 1,500 seconds, using the defined time intervals. The results from the irregular ceiling method can now be compared directly with those produced by the regular ceiling method.

DATA ANALYSIS

BOCA National Building Code Commentary Examples

In order to check the evaluation method, the examples presented in the 1993 *BOCA National Building Code Commentary* were entered into the spreadsheets. Each example used a 2,000-Btu/s (2,110-kW) heat release rate.

Example 1 Example 1 illustrates the regular ceiling method applied to a 2,500-ft^2 (232-m^2) atrium, 50 ft (15 m) high ($A/H^2 = 1$). In this case, the regular ceiling method equation was used to determine the need for a smoke management system. Figure 6 displays the results of the calculations and graphically shows the -28 ft (-8.5 m) predicted smoke layer interface height using Equation 1.

Note the following characteristics that are displayed in Figure 6 and are repeated in all cases:

- The characteristic shapes of the curves remain the same, regardless of the area or aspect ratio of the space. The irregular ceiling method curve is asymptotic with respect to the floor (x-axis) of the space, while the regular ceiling method curve will always intersect the x-axis.
- The two curves cross. The reason for this is that the regular ceiling method equation predicts an infinite height as time approaches zero.
- At the point at which the curves cross, both methods return the same time for the same height. However, as the curves descend, the difference in time between the regular ceiling method and the irregular ceiling method becomes more pronounced.

In this particular example using the 20-minute criteria, both methods would require a smoke management system.

Example 2 Figure 7 represents a comparison of the results produced by the two methods in a 100,000-ft^2 (9,290-m^2) atrium, 100 ft (30 m) in height ($A/H^2 = 10$).

The Commentary uses this example, again calculated using Equation 1, to show the need for a smoke management system when the critical height is assumed at 40 ft (12 m).

Figure 7 supports this conclusion using the regular ceiling method and illustrates the calculated value of 33.9 ft (10 m) presented in the Commentary.

However, the results differ markedly when the irregular ceiling method is used. Note that, at the 40-ft (12-m) height, using the irregular ceiling method, the smoke layer interface arrival time is between 1,700 and 1,800 seconds vs. the 900- to 1,000-second time predicted by the regular ceiling method.

Examples such as these illustrate the significant differences in times predicted by the two methods. Table 2 displays the predicted times when the smoke layer interface passes through 10-ft (3-m) height intervals and compares the regular ceiling method and irregular ceiling method predictions. Note the time difference of 760 seconds at the selected design height of 40 ft (12.1 m).

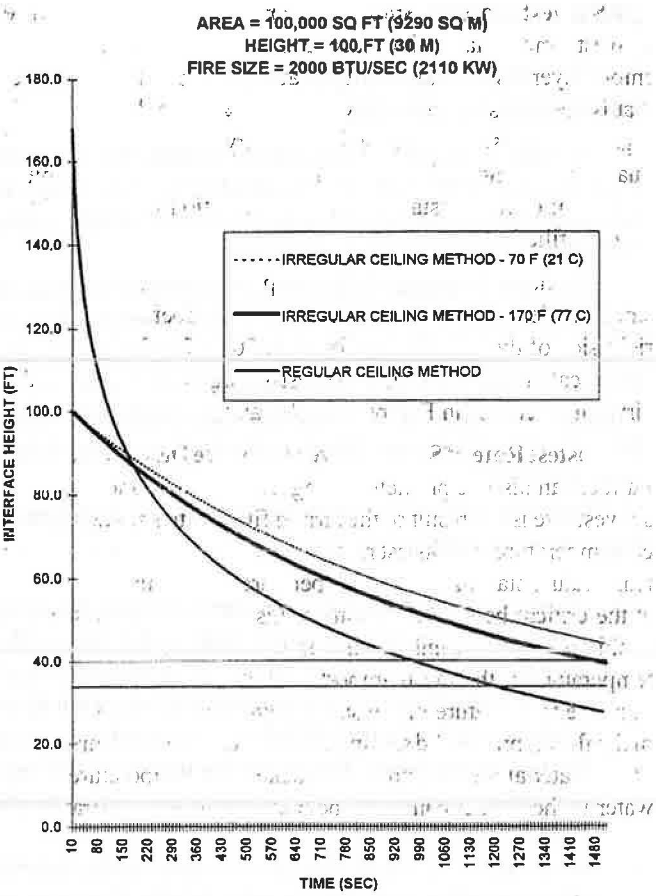

Figure 7 *Comparison of results produced by two methods in 100,000 ft² (9,290 m²) atrium.*

TABLE 2
Differences in Predicted Times Using Regular vs. Irregular Ceiling Methods

	Time (s)		
Height	***t* (regular)**	***t* (irregular)**	**Δt**
90 ft (27 m)	163	150	(13)
80 ft (24 m)	230	335	105
70 ft (21 m)	330	560	230
60 ft (18 m)	470	840	370
50 ft (15 m)	675	1215	540
40 ft (12 m)	970	1730	760
30 ft (9 m)	1380	2500	1120
20 ft (6 m)	1975	3810	1835

Analysis of Selected Atrium Areas and Aspect Ratios

Characteristic Smoke Layer Interface Descent Curves—Regular Ceiling Calculation Method Figure 4 illustrates the family of characteristic curves produced by Equation 1 for a 50,000-ft² (4,645-m²) atrium with aspect ratios of 0.9, 10, and 14. The fire size of 4,400 Btu/s (4,645 kW) is constant. Note the shift of the curves toward the y-axis as the height of the space increases. This reflects the influence of placing the H term in the denominator of Equation 6. Note the two lower heights, 71 ft (22 m) and 60 ft (18 m). At these heights the differences in filling times are not as apparent, and the curves could be seen as being comparable. The crossing point of the two lower curves occurs at approximately 1,000 seconds, where their slopes are nearly identical and where the continuations of the two curves are nearly indistinguishable. Contrast this with the crossing point of the 235-ft (72-m) curve, where the slopes are noticeably different. The differing slopes at the same height mean that Equation 1 is predicting different rates of smoke production for the same height, with larger rates of smoke production in taller buildings. These curves present a counterintuitive situation, where taller spaces are predicted to fill faster than shorter ones.

Using Figure 4, consider the following hypothetical atrium:

H = 235 ft (72 m)
A = 50,000 ft² (4,645 m²)
Q = 4,400 Btu/s (4,640 kW)
Z_{CR} = 15 ft (4.5 m)

A smoke management system is required if the smoke layer interface reaches the critical height in less than 1,200 seconds.

Question 1—How long does it take the smoke layer interface to reach the critical height?

Answer—Seven hundred seconds (from spreadsheet data). Therefore, a smoke management system is required.

Instead of a smoke management system, the designer decides to install a horizontal shutter at the 71-ft (22-m) level and close the shutter when the smoke layer interface reaches this height.

Question 2—How long does it take the smoke layer interface to reach the critical height if the shutter is closed when the interface reaches the 71-ft (22-m) level?

Answer—The time required to reach the 71-ft (22-m) level is 300 seconds (from spreadsheet data for the 235-ft [72-m] curve). Once the shutter is closed, the space becomes a 71-ft (22-m) atrium, and the 71-ft (22-m) curve is used to predict the time of descent to the critical height. This time is 915 seconds (from spreadsheet data). Therefore, the combined time with the shutter in place is 1,215 seconds. No smoke management system is required, and the shutter has delayed the arrival of the smoke interface by more than 500 seconds.

It should be noted that the example using the shuttered atrium uses Equation 1 at or above the point where $Z/H = 0.2$ for both heights, and such an approach would be within the parameters of NFPA 92B (1995). In the context of this paper, it is intended to illustrate an inherent limitation in the use of Equation 1 for spaces significantly taller than those referenced in NFPA 92B (1995) yet within the specified aspect ratios. This example illustrates the potential logical flaw in Equation 1. However, this characteristic is not evident to the user since design occurs one building at a time.

Characteristic Smoke Layer Interface Descent Curves—Irregular Ceiling Calculation Method Figure 5 illustrates the family of characteristic curves produced by the combination of Equations 10 and 13 for a 50,000-ft^2 (4,645-m^2) atrium with aspect ratios of 0.9, 10, and 14. The fire size of 4,400 Btu/s (4,645 kW) is constant. Note the shift of the curves away from the y-axis as the height of the space increases.

Now consider the same hypothetical problem posed earlier. In the 235-ft (72-m) space it would be necessary to extend the curve to 2,115 seconds before the smoke interface layer reached the critical height. Of this time, the first 545 seconds (vs. 300 seconds in the regular ceiling calculation) would be required to descend to 71 ft (22 m). The 71-ft (22-m) curve predicts a time of 1,570 seconds to reach the critical height of 15 ft (4.5 m). Thus, the combined time using the two curves is 2,115 seconds, identical to the time predicted by the 235-ft (72-m) curve. There is no perceived benefit to closing off part of the atrium as the smoke layer interface descends. Equation 10 will have the same slope (rate of smoke produced) at a given height regardless of the height of the enclosure.

Note the diverging trend between the predicted filling times in Figures 4 and 5, which will tend to produce greater predicted differences for taller spaces. As noted previously, the tests referenced by NFPA 92B in the development of Equation 2 did not include filling times for spaces greater than 86 ft (26.3 m) in height. Yet, NFPA 92B (1995, Appendix E) and the 1993 BOCA Commentary (example 2) utilize the method for heights that exceed those in the documented tests. This is not the case for fire sizes and atrium aspect ratios, where the "where used" tends to agree with the "where tested."

Assessment of Data for Aspect Ratios of 0.9 and 14 The spaces defined in Table 1 were evaluated using the regular ceiling and irregular ceiling calculation methods. In each case, results are graphically produced for the 2,000-Btu/s (2,110-kW) and 4,400-Btu/s (4,640-kW) design fires described in the 1996 BOCA Code. The smoke layer interface position predicted by Equation 1 and (combined) Equations 10 and 13 can be directly compared.

In all cases, the two methods produce curves that cross at a single point, then diverge by increasing amounts as the smoke layer interface descends. Table 2 illustrates this behavior, based on the 1993 BOCA Code Commentary example.

RECONCILIATION OF THE TWO CALCULATION METHODS

There is a need to reconcile the two divergent calculation methods. Until more research and test data become available, design professionals need to be confident that they can approach this calculation and know the boundaries of the methodology.

Sensitivity Analysis—Equation 10

In order to understand the differences between the two predictive methods, a sensitivity analysis will be done using the volume flow equation (Equation 10). The sensitivity analysis will attempt to define the fastest and the slowest smoke layer interface descent times predicted by this method for the cases selected.

Slowest Rate of Smoke Layer Interface Descent. The slowest smoke layer interface descent will occur when the smoke layer temperature approximates the ambient temperature; that is, there is sufficient buoyancy to get the smoke to the ceiling, but no density correction is necessary. As each incremental quantity of smoke is added, it also approximates ambient temperature. It is assumed that this condition exists until the space is filled.

Equations 10 and 13 inherently produce the slowest filling since the density correction inherent to the coefficients on the right side of the equations is for air at 70°F (21°C). The results of the calculations for this slowest-filling calculation are the "irregular" curves in Figures 8, 9, 10, and 11.

Fastest Rate of Smoke Layer Interface Descent. The fastest rate can also be predicted using Equations 10 and 13. If the slowest rate is the result of the atrium filled with smoke at ambient temperature, the fastest rate will occur when the smoke layer temperature stabilizes at the temperature of the plume measured at the critical height. To illustrate this concept, turn Figure 1c upside down and think of this as water filling a bucket. The temperature at the tap is important, but the distance the water falls, the temperature of the surrounding air, and the dispersion of the flow (spray, solid stream, etc.) will change the temperature of the water along its path to the bucket. The temperature of the water in the bucket can never be hotter than the temperature of

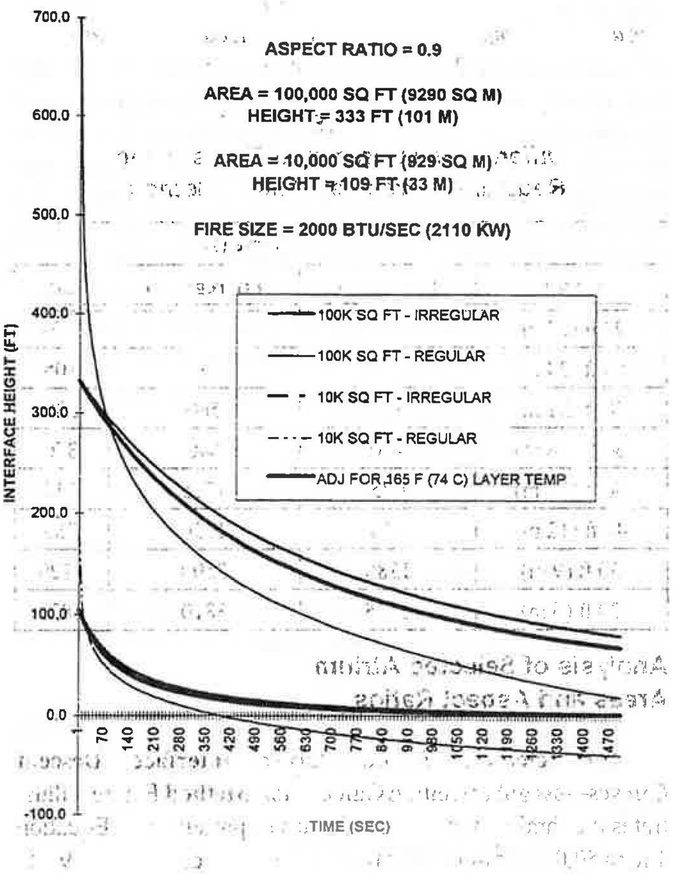

Figure 8

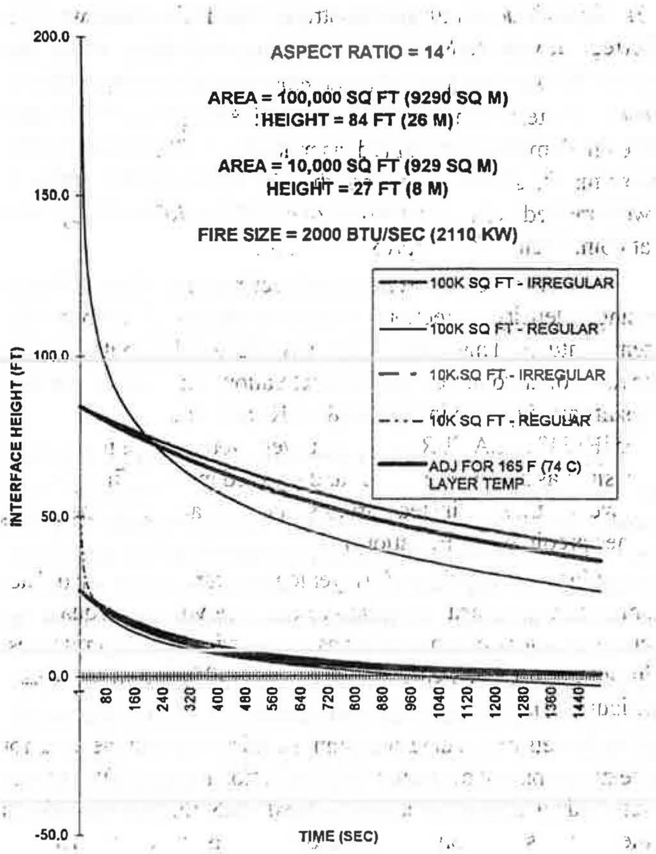

Figure 9

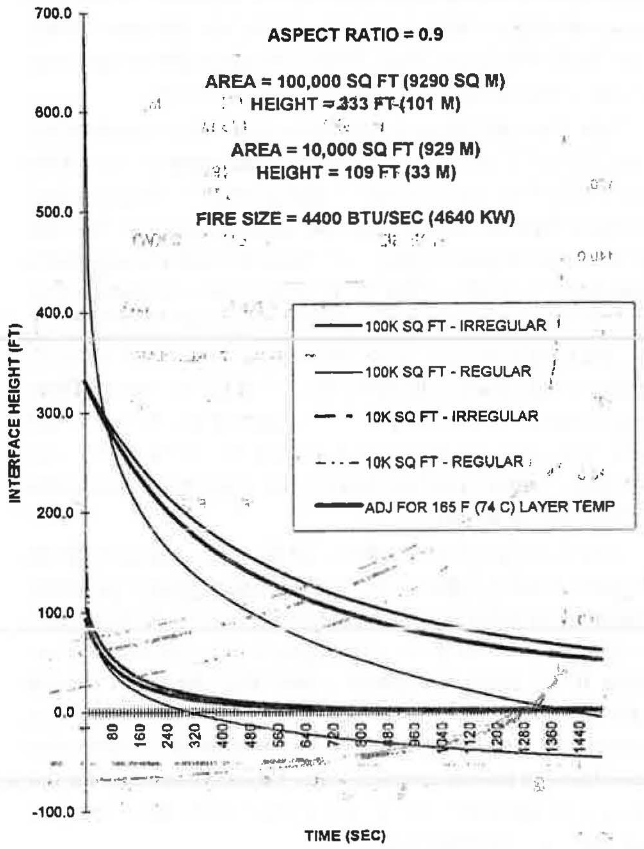

Figure 10

the water as it enters the accumulated layer. In the case of a fire in an atrium, the fire represents the liquid as it leaves the tap, and the smoke layer interface represents the surface of the water in the bucket. Therefore, the most conservative method for estimating the average temperature of the smoke layer is to assume that the entire layer has reached the temperature of the smoke plume centerline temperature, measured at the critical height.

The comparison will be done using the *BOCA National Building Code Commentary* example previously cited and illustrated by Figure 7. The critical height will be 40 ft (12 m). To perform this calculation, it is necessary to begin with the mass flow equation from NFPA 92B:

$$m = 0.022Q_c^{1/3}Z^{5/3} + 0.0042Q_c. \quad (11)$$

This must be done because Equation 10 has an imbedded density correction based on 70°F (21°C).

Next, the centerline plume temperature is approximated by the following correlations (Klote 1994b):

$$T_{cp} = T_a + 338\left[\frac{Q_c^{2/3}}{(Z_{CR} - Z_0)^{5/3}}\right] \quad (18)$$

where

T_a = ambient temperature (°F),

T_{cp} = plume centerline temperature (°F),

Z_0 = elevation of virtual origin above the top of the fuel (ft),

and

$$Z_0 = 0.278Q^{2/5} - 1.02D_f \quad (19)$$

where

D_f = diameter of fire (ft).

For this example, a heat release rate of 2,000 Btu/s (2,110 kW) is assumed. To create the steady-state burning, it will be further assumed that the fuel is a burning liquid in a pan of sufficient depth to sustain continuous burning. The liquid's heat release rate will be assumed to be 290 (Btu/s)/ft^2 (3,300 kW/m^2). This is equivalent to a surface area of approximately 7 ft^2 (0.65 m^2).

Converting from area to diameter,

$$D_f = 3\text{ ft } (0.9\text{ m}),$$

and substituting into Equation 19,

$$Z_0 = 2.75\text{ ft } (0.84\text{ m}).$$

The plume centerline temperature at the critical height is calculated as

$$T_{cp} = 170°\text{F } (77°\text{C}).$$

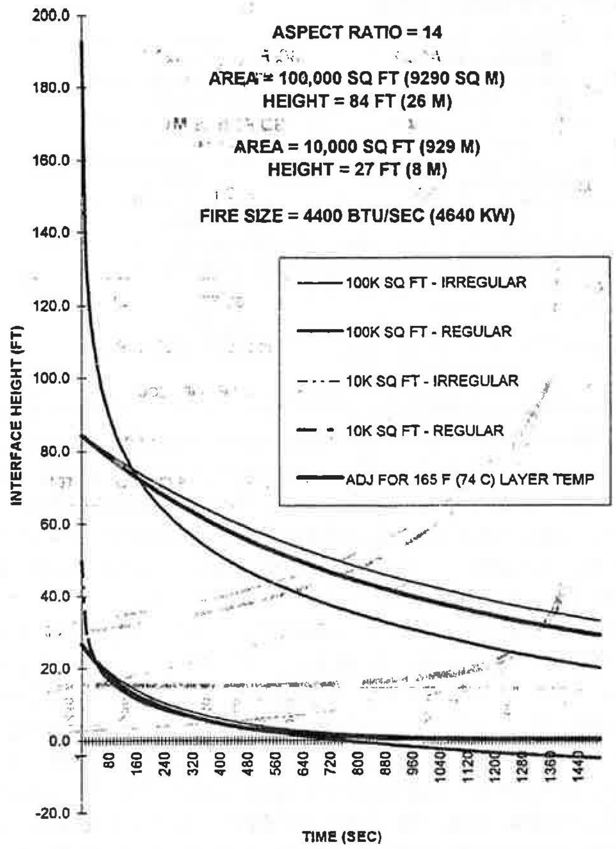

Figure 11

(If, as assumed, the entire layer is at this uniform temperature, sprinkler operation could be expected if standard 165°F [74°C] sprinklers are installed.)

Using the following to calculate the density of smoke at 170°F (77°C),

$$\rho = \frac{0.081}{0.002T_{cp} + 0.935} \qquad (20)$$

and substituting 170°F (77°C) for T_{cp},

$$\rho = 0.0635 \text{ lb/ft}^3 \ (1.019 \text{ kg/m}^3).$$

Again, beginning with the mass flow equation,

$$m = 0.022Q_c^{1/3}Z^{5/3} + 0.0042Q_c. \qquad (11)$$

Convert to volume flow using the relationship

$$V = 60m/\rho. \qquad (12)$$

The rate of smoke production (cfm) will be

$$V = 20.8Q_c^{1/3}Z^{5/3} + 3.97Q_c. \qquad (21)$$

This will represent a uniform layer temperature equal to the temperature of the plume centerline at the critical height. Note that this is similar to the equation in the 1993 *BOCA National Building Code*. Figure 7 illustrates this filling rate with the "Irregular Ceiling Method—170°F (77°C)" curve.

The two "irregular" method curves will represent the slowest and fastest filling times for this particular space. Note that the "regular" method curve predicts much faster filling times. (Also note that its shape is similar to the 170°F [77°C] curve, and if it were moved vertically it would overlay the 170°F [77°C] curve at points below Z/H approximating 0.7.)

All of the other areas and aspect ratios were reevaluated using a density correction based on 165°F (74°C) smoke layer temperatures. This temperature was selected due to its approximation of automatic sprinkler activation temperatures. These results are depicted in Figures 8, 9, 10, and 11 as the "ADJ FOR 165°F (74°C) LAYER TEMP" curves. Note that the new smoke density has shifted the curves and resulted in faster filling times. However, these adjusted curves still do not approach the filling times predicted by Equation 1.

Since the 165°F (74°C) layer temperature correction did not shift the curves nearly enough to coincide with the Equation 1 curves, some additional time was spent reviewing the limited test information contained in NFPA 92B (1995), Table A-3.6.2.2 (Figure 12).

Six sets of test data are summarized as forming the basis for the development of the regular calculation method. Of these six sets of data, two new sets were added for NFPA 92B (1995). In the author's opinion, only two of the tests were conducted in rooms large enough to be considered atria with heat release rates comparable to expected design fires. One of these tests was conducted in a 7,750-ft^2 (720-m^2) room, 86 ft (26.3 m) high, and the other was in a 19,500-ft^2 (1,815-m^2) room, 41 ft (12.5 m) high. The fire size in the 86-ft (26.3-m) room was 1,230 Btu/s (1,300 kW). The fire size in the 41-ft (12.5-m) room was 7,580 Btu/s (8,000 kW). None of the remaining referenced test data appears to be "large-scale experimental programs in tall ceiling spaces" as described by NFPA 92B. To this author, the remaining tests appear to be scale models of atrium spaces, and any predicted results should be viewed as such.

The scaling ratios provided in NFPA 92B, Section 3-1.2.2, provide a way to convert the NFPA 92B referenced tests to a

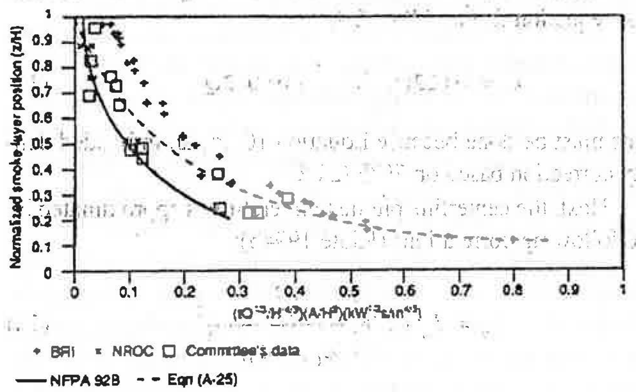

Figure 12 *Distribution of NFPA 92B test data.* ©*1996 NFPA.*

TABLE 3
Test Fires Converted to Atrium Size Enclosures

Referenced Test	Model Height	Model Fire	Building Height	Building Fire
BRI (50)	86 ft (26.3 m)	1232 Btu/s (1300 kW)	120 ft (37 m)	2146 Btu/s (2264 kW)
NRCC (51)	41 ft (12.5 m)	7582 Btu/s (8000 kW)	120 ft (37 m)	45400 Btu/s (47.9 MW)
Sandia, Test 7 (10)	20 ft (6.1 m)	489 Btu/s (516 kW)	120 ft (37 m)	9780 Btu/s (10.3 MW)
Mullholland (53)	7.9 ft (2.4 m)	15 Btu/s (16.2 kW)	120 ft (37 m)	1363 Btu/s (1472 kW)
Cooper (54)	7.9 ft (2.4 m)	24, 95, 213 Btu/s (25, 100, 225 kW)	120 ft (37 m)	2181, 8636, 19363 Btu/s (2.3, 9.1, 20.5 MW)
Hagglund (55)	20 ft (6.15 m)	265 Btu/s (280 kW)	120 ft (37 m)	5300 Btu/s (5600 kW)

single baseline height. These may be summarized as follows, where each of the referenced tests is converted to an equivalent "atrium" of a common height, in this case 120 ft (37 m). This height is selected because it has been used in the NFPA 92B examples.

NFPA 92B (NFPA 1991, Section 3-1.2) provides the following scaling ratios for heights and fire sizes:

$$Q_m/Q_b = (H_m/H_b)^{5/2} \qquad (22)$$

where

Q_m = heat release rate (model),
Q_b = heat release rate (building),
H_m = height (model), and
H_b = height (building).

Table 3 converts the NFPA 92B referenced test information into buildings of identical heights.

Note the fire sizes in the last column of Table 3. Of these fire sizes, only BRI, Mullholland, Cooper (24 Btu/s), and Hagglund represent design conditions comparable to those provided in the *BOCA National Building Code*. All of the other tests represent much larger fires when inserted into the 120-ft (37-m) space. This suggested that layer temperatures higher than 165°F (74°C) may have been inherent in the development of the correlation and that the correlation is compensating for layer temperatures far higher than will be present in common atrium design scenarios.

The likely difference between the two calculation methods became apparent. Equation 1 is predicting smoke layer interface descent based on a much higher temperature than 165°F (74°C). The higher temperature would have to be in the hundreds of degrees, as would be expected with a 7,580-Btu/s (8,000-kW) fire in a 41-ft (12.5-m) room. This would also be the case for some of the lower-ceilinged rooms, albeit with smaller fires.

Figure 12 shows the distribution of the raw test data referenced by NFPA 92B. Note the distribution of the "+" symbols, based on data from the BRI test, one of which reflects appropriate scaling for the 120-ft (37-m) atrium. Note that these data begin to the right of the mass-based flow curve (dashed line), probably due to the time required for the layer to form. Then note its correlation with the mass-based curve. It is not known if NFPA 92B corrected this curve for increased layer temperature (decreasing smoke density) conditions. It is the author's opinion that the curve probably represents an uncorrected curve. If this curve were corrected for the changing smoke density, it may track the test data in a consistent way all the way down to the end of the data collection, with each predicted data point a consistent number of seconds to the left of the measured data reflecting the layer formation time. Also note the distribution of the "x" symbols, based on data from the NRCC test, comparable to a 45,400-Btu/s (47.9-W) fire in the 120-ft (37-m) atrium. These data track the NFPA 92B correlation favorably, with little perceptible layer formation time, as would be expected for such a large fire in the 120-ft (37-m) space. It is not possible to distinguish committee data as represented by each of the "" symbols, but by reviewing the "building" fire sizes above, it would be the author's opinion that their positions could be predicted by their heat release relationship to the BRI and NRCC data. NFPA 92B provides no way to confirm this.

To test this assumption, a 10,000-ft^2 (929-m^2), 32-ft (10-m) room and a 100,000-ft^2 (9,290-m^2), 100-ft (30-m) room (aspect ratio = 10) were recalculated using the 2,000 Btu/s (2,110-kW) fire. In this case, the plume centerline temperature calculation was performed for a critical height of 20 ft (6 m), representing a Z/H of 0.625 for the 10,000-ft^2 (929-m^2) room and a Z/H of 0.2 for the 100,000-ft^2 (9,290-m^2) room.

$$T_{cp} = T_a + 338\left[\frac{Q_c^{2/3}}{(Z_{CR}-Z_0)^{5/3}}\right]. \qquad (18)$$

Using

T_a = 70°F (21°C),
Q_c = 1,400 Btu/s (1,475 kW),
Z_{CR} = 20 ft (6 m), and
Z_0 = 2.75 ft (0.84 m),

the plume centerline temperature is

$$T_{cp} = 437°F\ (225°C)$$

and the smoke density becomes

$$\rho = 0.045\ lb/ft^3\ (0.722\ kg/m^3).$$

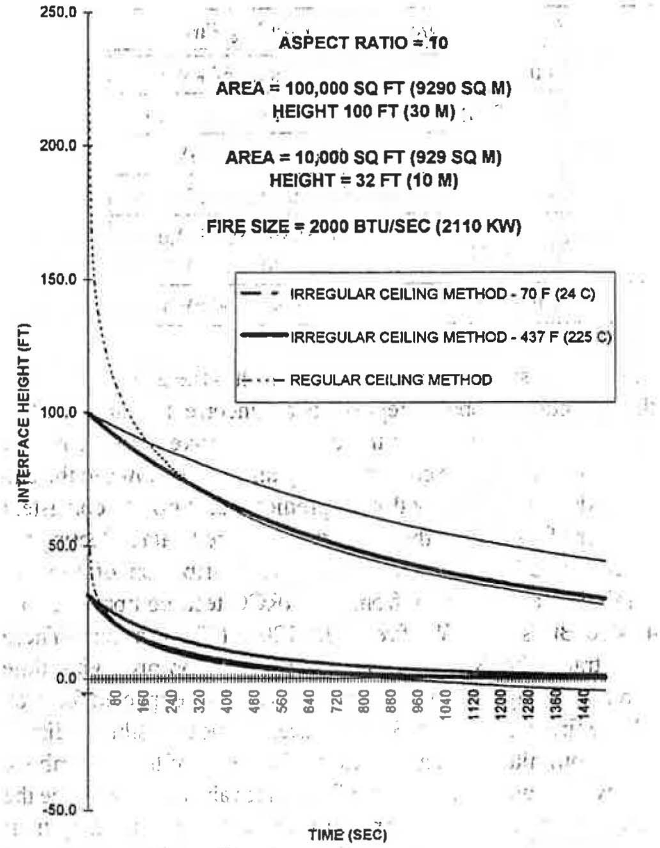

Figure 13

This creates a new mass flow equation above the flame height of

$$V = 29.3Q_c^{1/3}Z^{5/3} + 5.6Q_c \quad (23)$$

and a new mass flow equation below the flame height of

$$V = 27.7Q_c^{3/5}Z \quad (24)$$

Using these equations in place of Equations 10 and 13, a new set of data was generated for this much higher layer temperature.

Figure 13 shows the remarkable correlation between the regular and irregular ceiling methods when the increased layer temperature is factored into the irregular ceiling calculation method. This appears to be the reason for the wide variance between the methods and seems to be supported by the test data referenced in NFPA 92B.

Sensitivity Analysis—Equation 1

This paper summarized some of the characteristics associated with the use of Equation 1 in previous discussions. One important characteristic of Equation 1 is that it is derived from a correlation, or a best fit of a limited data set. Only two sets of data were from rooms large enough to be considered atria (author's opinion). From these two sets of large room data and a second group of data from much smaller enclosures, a correlation was created that is now being applied to some very large spaces.

If Equation 1 is an accurate predictor of smoke filling an enclosure, then our reliance on the existing plume entrainment and mass flow correlations is misplaced. If, on the other hand,

TABLE 4
Adjusted Initial Term Values - 2000 Btu/s (2110 kW) Heat Release Rate

	A/H^2	
Area	**0.9**	**14**
100,000 ft^2 (9290 m^2)	0.84	0.81
10,000 ft^2 (929 m^2)	0.84	0.78

TABLE 5
Adjusted Initial Term Values - 4400 Btu/s (4645 kW) Heat Release Rate

	A/H^2	
Area	**0.9**	**14**
100,000 ft^2 (9290 m^2)	0.84	0.81
10,000 ft^2 (929 m^2)	0.84	0.75

Equation 1 has inherent flaws that make its use less desirable in tall spaces, then it needs to be reworked.

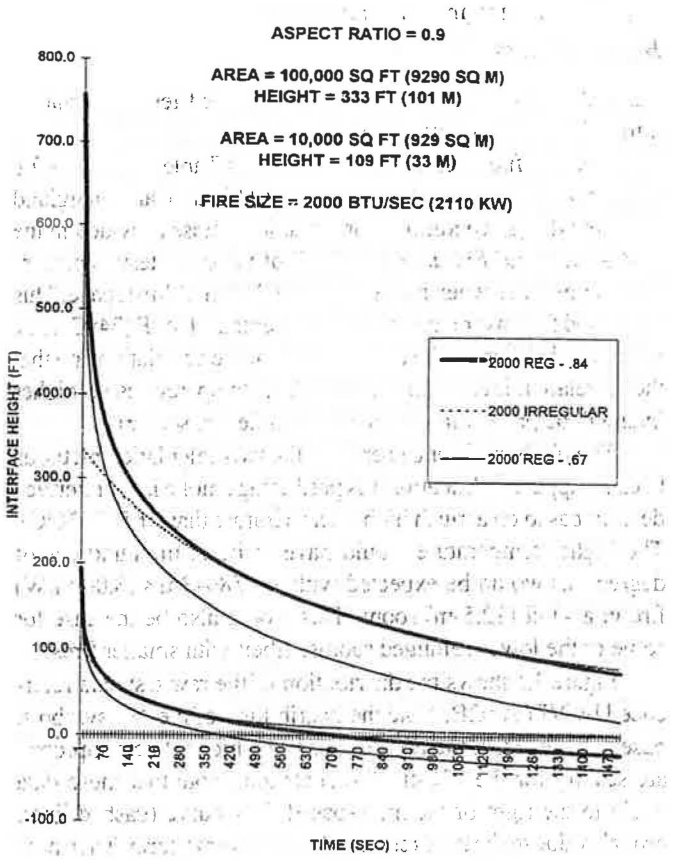

Figure 14

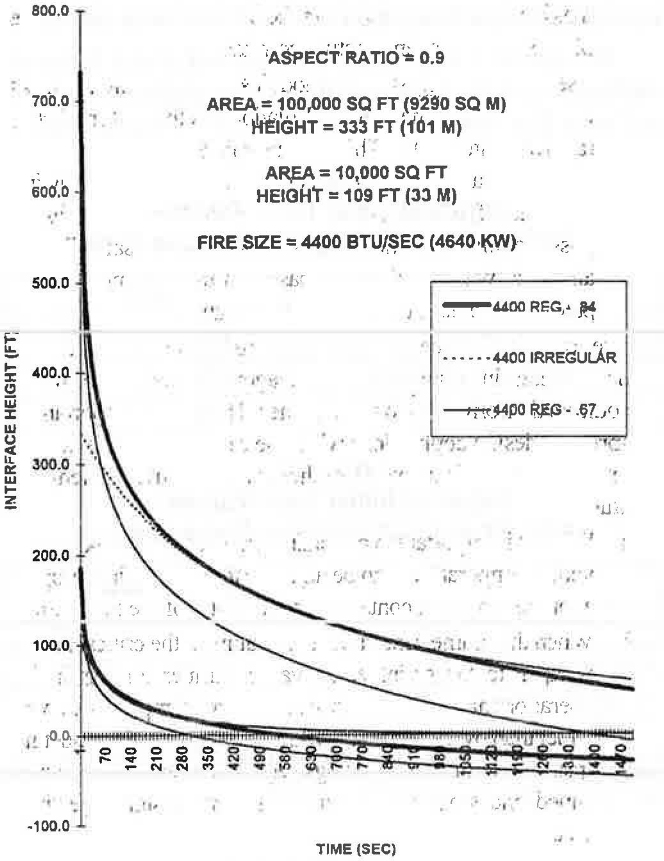

Figure 15

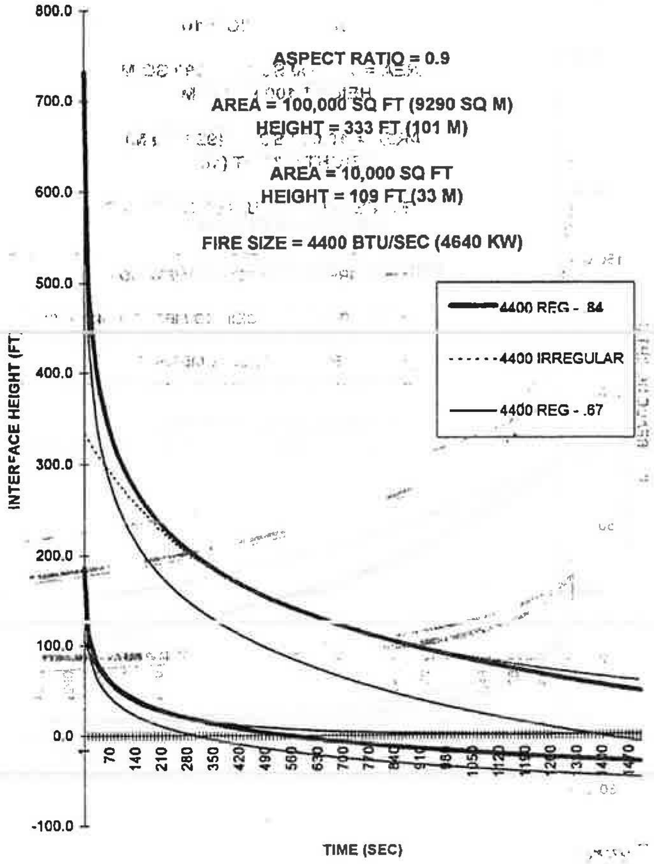

Figure 16

From the previous analysis, Equation 1 appears to have limited use in taller spaces due to its seemingly high inherent layer temperature assumption. Perhaps it would be more useful if the mandated design fires were much larger.

If Equation 1 is to be continued in use, it will have to be modified to reflect the lower layer temperatures in current atrium design. By observation, the Equation 1 curves are relatively similar in shape to the curves produced by the mass flow equations. By adjusting the initial term of Equation 1 (0.67), the curves can be brought into close alignment with the 70°F (21°C) irregular ceiling method curves. Tables 4 and 5 are some suggested modifying factors, and Figures 14, 15, 16, and 17 illustrate the adjusted Equation 1 curves. Note the increase in the initial term as the height of the space increases.

CONCLUSIONS

1. The regular ceiling calculation method and the irregular ceiling calculation method in the 1996 *BOCA National Building Code* do not produce equivalent results when utilized within the limitations described. Their use should not be presented as being equivalent.
   a. Differences in predicted times can be nearly 100% in certain area/aspect ratio combinations. These differences occur in foreseeable design situations
   b. There are foreseeable conditions where the use of the regular ceiling method will require a smoke management system and the use of the irregular ceiling method will not. The example in the BOCA Code Commentary illustrates this point. This can lead to inconsistent application of the Code, confusion on the part of design professionals, and significant cost consequences.
   c. Since nearly every atrium has some variation in horizontal cross-sectional area or, in new buildings, some amount can be designed in, designers have the ability to create varying horizontal cross-sectional areas in order to utilize the "slower" approach.
   d. Since nearly every irregular atrium can be simulated by some sort of regular "flat" shape, building officials, fire officials, and other authorities having jurisdiction have the ability to insist on the use of the "faster" approach.
2. The irregular ceiling method is likely to predict a slower than observed smoke layer interface descent, while the regular ceiling method is likely to predict a faster than observed descent. The reasons for this conclusion are as follows:
   a. The regular ceiling method has an inherent smoke density correction based on layer temperatures observed with large fires in relatively short rooms. These conditions are not likely to exist in most design situations because (1) in shorter rooms, generally less than 40 ft (12 m) tall, 165°F (74°C) sprinklers

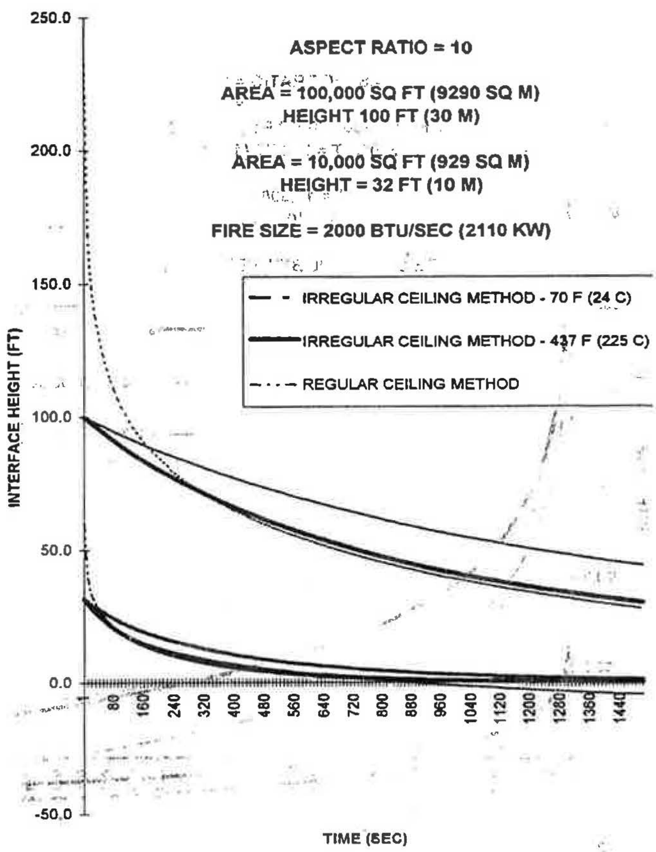

Figure 17

are likely to operate due to the anticipated plume centerline temperatures when the design fire is 2,000 Btu/s (2,110 kW) or higher, and (2) in taller rooms, critical heights will be such that the smoke layer temperature will not reach the temperatures that seem to be inherent in this method.

b. The irregular ceiling method will tend to predict a slower than observed smoke layer interface descent because there is no layer temperature correction in the volume flow equation.

3. In order to continue to use either calculation method, a correction factor will need to be included that will permit the designer to compensate for the anticipated smoke layer temperatures that will be encountered in atrium smoke management system design situations. This paper suggests a methodology for making corrections to the "regular" or the "irregular" calculation methods.

   a. "Regular" calculation method—For the "regular" calculation method, it is necessary to develop a number of tables corresponding to various atrium aspect ratios, heat release rates, and critical heights. Tables 4 and 5 illustrate the adjustment of the initial term values to align the "regular" calculation method results with the "irregular" calculation method results for an assumed layer temperature of 70°F (21°C), corresponding to a relatively high critical height. For lower critical heights, different initial term values are necessary.

   b. For the "irregular" calculation method, Equations 10 and 13 must be adjusted to reflect layer temperatures higher than 70°F (21°C). To do this, it is suggested that an anticipated maximum layer temperature be calculated based on the plume centerline temperature correlation.

   Use of this suggested methodology will result in direct comparison of the two calculation methods for $Z/H <$ (approximately) 0.8. This will permit designers to use the "pass-fail" approach with a degree of confidence, knowing the limits of the method. This method will predict the fastest possible filling and should allow for a "factor of safety" since all filling will be calculated based on the minimum anticipated smoke density at the critical height.

4. Use of a plume centerline temperature correlation for the design fires in atrium smoke management systems provides additional information to the designer. This can be important in sprinkler design applications when the calculated plume centerline temperature is in excess of the sprinkler activation temperature.

   a. When it is important to maintain egress routes, sprinkler activation temperatures can be adjusted to avoid sprinkler operation due to direct contact with the center of the fire plume.

   b. When the plume centerline temperature at the critical height is equal to the sprinkler activation temperature, sprinkler operation may occur due to the increasing temperature layer, rather than by direct contact with the fire plume. By adjusting sprinkler temperature ratings, egress routes can be maintained and smoke management system design objectives met.

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