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Prediction of Smoke Movement in Atria: Part II—Application to Smoke Management

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ABSTRACT

In recent years, approaches to smoke management in atria have been introduced into many codes and engineering guides. This paper presents information that can be used for design analysis of atrium smoke management systems. Various approaches to manage smoke in atria are discussed. Often a hot layer of air forms under the ceiling of an atrium, and this hot layer can prevent smoke from reaching the ceiling. A method is discussed for dealing with smoke detection when such a hot air layer prevents smoke from reaching the ceiling. Commissioning is needed to ensure that smoke control systems will function as intended during fire situations. Commissioning efforts should start before design and extend until maintenance system modifications after construction are finished. Research is needed concerning (1) the use of airflow for smoke control between the atrium and communicating spaces and (2) the depth of the smoke layer required to prevent atrium exhaust from pulling air from the lower layer.

INTRODUCTION

In recent years, approaches to smoke management in atria have been introduced into codes and engineering guides (BOCA 1993; UBC 1993; NFPA 1991; Klote and Milke 1992; Hansell and Morgan 1994). While these basic approaches differ in many respects, they all have the zone fire model concept as a common foundation and consist of a collection of algebraic equations intended for design calculation. For simplicity, discussion of the basic approaches is limited to those of NFPA 92B (1991). However, much of this applies to the other approaches as well.

This paper is the second of a two-part series about smoke movement in atria. The first part (Klote 1997) explained the physical concepts of the steady fire, unsteady fire, zone fire model, and the fire plume that are the basis of atrium smoke management. Part II presents information that can be used for analysis of smoke movement for design of atrium smoke management systems. A computer program, entitled Atria Smoke Management Engineering Tools (ASMET), was written consisting of a set of equations that may be of help for conventional atrium designs (Klote 1994). This program is available at no cost from the author.

The basic calculation methods of this paper are not applicable when the design exceeds the range of applicability of the equations presented or when obstructions in an atrium do not allow flow. For these situations, there may be benefit to computational fluid dynamic (CFD) modeling or physical modeling. CFD modeling and physical modeling provide greater information than usual design methods but require specialized and advanced engineering training. Introductory information about these topics is provided by Klote (1994).

As with part I, the term "atrium" is used in this paper in a generic sense to mean a large space such as an atrium, an enclosed shopping mall, a sports arena, or an exhibition hall. NFPA 92B (NFPA 1991) and the smoke control design book by Klote and Milke (1992) define smoke as the airborne solid and liquid particulates and gases evolved when a material undergoes pyrolysis or combustion, together with the quantity of air that is entrained or otherwise mixed into the mass.

APPROACHES FOR SMOKE MANAGEMENT

Most atria smoke management systems are designed with the goal of avoiding occupant exposure to smoke during evacuation.[1] The following are approaches that can be used to manage smoke in atria.

1. **Filling with a Steady Fire:** This approach consists of allowing smoke to fill the atrium space while occupants

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[1] An alternative goal could be to avoid subjecting occupants to untenable conditions. Possibly the reason that this approach is not commonly accepted is the reluctance of engineers to design systems that expose occupants to any smoke. even if that exposure is not lethal.

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evacuate the atrium. This approach applies only to large-volume spaces where the smoke-filling time is sufficient for both decision making and evacuation. For information about people movement during evacuation, the reader is referred to Nelson and MacLennan (1988) and Pauls (1988). The smoke-filling calculations are based on a steady design fire, and these calculations can be done by the computer zone fire models discussed above or by application of the *steady filling equation* presented in the next section.

2. **Filling with an Unsteady Fire:** The comments for approach 1 apply except that the fire is unsteady. The *unsteady filling equation* presented later is applicable to a fire whose heat release is proportional to the square of the time from ignition. Such a fire is called a *t-squared fire* and is described in part I. As with approach 1, the smoke-filling calculations can also be done by computer zone fire models. The computer approach allows simulation of filling by other than t-squared fires.
3. **Steady Clear Height with Upper Layer Exhaust:** This approach consists of exhausting smoke from the top of the atrium in order to achieve a steady clear height for a steady fire (Figure 1). A calculation method based on the plume equations above is presented later. Computer zone fire models can also be used for these calculations.
4. **Unsteady Clear Height with Upper Layer Exhaust:** This approach consists of exhausting smoke from the atrium top at a rate such that occupants will have sufficient time for decision making and evacuation. The most convenient method of analysis for this design approach is by a computer zone fire model, and it is not discussed further in this paper.

Filling by a Steady Fire

The following experimental correlation of the accumulation of smoke in a space due to a steady fire is the *steady filling* equation from NFPA 92B (1991):

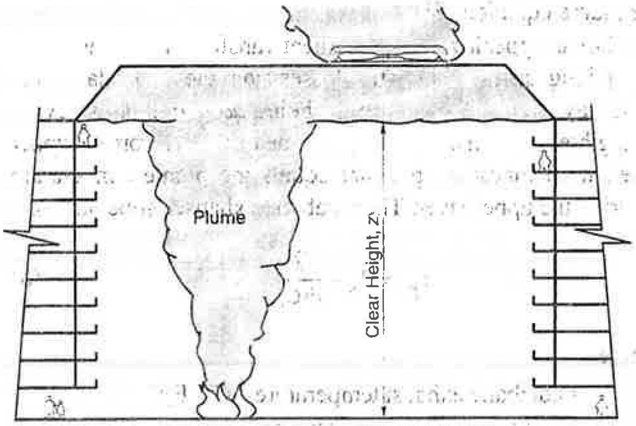

Figure 1 *Smoke exhaust to maintain constant clear height.*

$$\frac{z}{H} = C_{10} - 0.28\ln\left(\frac{tQ^{1/3}H^{-4/3}}{\frac{A}{H^2}}\right) \qquad (1)$$

where

z = height of the first indication of smoke above the fire, m (ft);
H = ceiling height above the fire, m (ft);
t = time, s;
Q = heat release rate from steady fire, kW (Btu/s);
A = cross-sectional area of the atrium, m² (ft²);
C_{10} = 1.11 (0.67).

This equation is conservative in that it estimates the height of the first indication of smoke above the fire rather than the smoke interface, as illustrated in Figure 2. In the idealized zone model, the smoke interface is considered to be a height where there is smoke above and none below. In actual fires there is a gradual transition zone between the lower cool layer and the upper hot layer. The first indication of smoke can be thought of as the bottom of the transition zone. Equation 1 is based on a plume that has no contact with the walls. Because wall contact reduces entrainment of air, this condition is conservative.

Equation 1 is for a constant cross-sectional area with respect to height. For other atrium shapes, physical modeling or CFD can be used. Alternatively, a sensitivity analysis can be made using the above equation to set bounds on the filling time for an atrium of complex shape. The equation is appropriate for A/H^2 from 0.9 to 14 and for values of z greater than or equal to 20% of H. A value of z/H greater than one means that the smoke layer under the ceiling has not yet begun to descend. These conditions can be expressed as

$$A = \text{constant with respct to } H,$$

$$0.2 \le \frac{z}{H} < 1.0,$$

and

$$0.9 \le \frac{A}{H^2} \le 14.$$

When Equation 1 is solved for z/H, the user will find that z/H is often outside the acceptable range. The steady filling equation can be solved for time.

$$t = \frac{A}{H^2}\frac{H^{4/3}}{Q^{1/3}}\exp\left[\frac{1}{0.28}\left(C_{10} - \frac{z}{H}\right)\right]. \qquad (2)$$

Filling by an Unsteady Fire

For a t-squared fire, the location of the smoke layer interface can be estimated by the *unsteady filling equation* from NFPA 92B (1991):

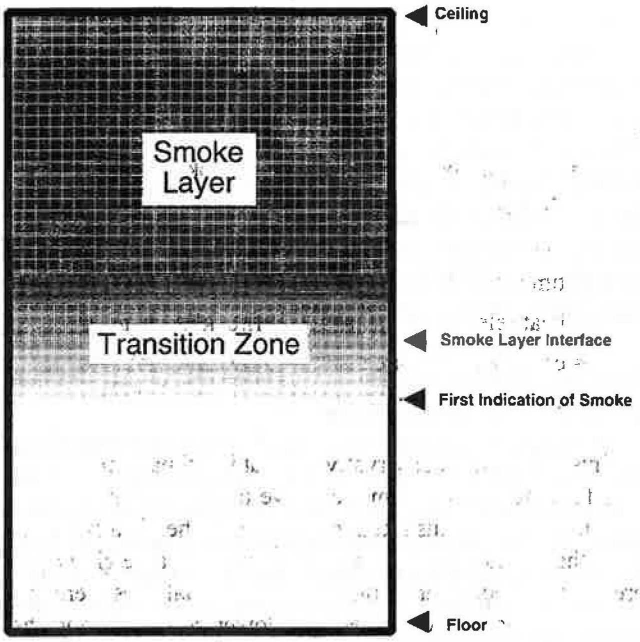

Figure 2 Smoke layer interface.

$$\frac{z}{H} = C_{11}\left[tt_g^{-2/5}H^{-4/5}\left(\frac{A}{H^2}\right)^{-3/5}\right]^{-1.45} \qquad (3)$$

where

z = height of the first indication of smoke above the fire, m (ft);
H = ceiling height above the fire, ft (m);
t = time, s;
t_g = growth time, s;
A = cross-sectional area of the atrium, m^2 (ft^2);
C_{11} = 0.91 (0.23).

This equation is also based on experimental data and is conservative in that it estimates the height of the first indication of smoke and is for a plume that has no wall contact.

Equation 3 is also for a constant cross-sectional area with respect to height, and the comments about atria of other shapes in the section above also apply to this section. The equation is appropriate for A/H^2 from 1.0 to 23 and for values of z greater than or equal to 20% of H. A value of z/H greater than one also means that the smoke layer under the ceiling has not yet begun to descend. These conditions can be expressed as

$$A = \text{constant with respect to } H,$$

$$0.2 \le \frac{z}{H} < 1.0,$$

and

$$1 \le \frac{A}{H^2} \le 23.$$

The growth time, t_g, has been discussed in part I, and values of it for various characteristic fire growths are listed in Table 2 of part I. As with the steady filling equation, the unsteady filling equation can be solved for time:

$$t = C_{12}t_g^{2/5}H^{4/5}\left(\frac{A}{H^2}\right)^{3/5}\left(\frac{z}{H}\right)^{-0.69} \qquad (4)$$

where C_{12} is 0.937 (0.363).

Steady Clear Height with Upper Layer Exhaust

The method of analysis presented in this section is based on several simplifying assumptions, and before using this method designers must verify that these assumptions are appropriate for their application.

As already stated, Figure 1 illustrates smoke exhaust from an atrium to maintain a steady clear height. A consequence of the steady clear height consideration is that the design fire must be of constant heat release rate. Consider that the only flow into the smoke layer is from the plume, and the only flow from the smoke layer is the smoke exhaust. From the principle of conservation of mass for a steady process, the exhaust flow must equal the flow from the plume. The simple plume equation (part I) can be used to calculate the exhaust flow rate, and this equation is listed below with variables redefined for this application:

$$\dot{m} = C_1 Q_c^{1/3} z^{5/3} + C_8 Q_c \qquad (5)$$

where

$\dot{m}$ = mass flow exhaust of exhaust air, kg/s (lb/s);
Q_c = convective heat release rate of fire, kW (Btu/s);
z = clear height above top of fuel, m (ft);
C_1 = 0.071 (0.022); and
C_8 = 0.0018 (0.0042).

The clear height is from the top of the fuel to the interface between the "clear" space and the smoke layer. As already stated, it is suggested that the top of the fuel be considered at the floor level to compensate for the uncertainties of the simple plume equation (Figure 1).

For an upper layer with little heat transfer to the atrium walls and ceiling and small radiative losses from the smoke layer, the upper layer can be thought of as being *adiabatic* or as having negligible heat transfer. If there is no heat transfer from the upper layer, the exhaust temperature equals the plume temperature entering the upper layer. The adiabatic exhaust temperature is

$$T_p = T_a + \frac{Q_c}{\dot{m}C_p} \qquad (6)$$

where

T_p = adiabatic exhaust temperature, °C (°F);
T_a = ambient temperature, °C (°F);
$\dot{m}$ = mass flow of exhaust air, kg/s (lb/s);
Q_c = convective heat release rate of fire, kW (Btu/s); and

C_p = specific heat of plume gases, kJ/kg·°C (Btu/lb·°F).

The density of the exhaust gases can be calculated from the perfect gas law:

$$\rho = \frac{p}{RT} \tag{7}$$

where

ρ = density of exhaust gases, kg/m^3 (lbm/ft^3);
p = absolute pressure, Pa (lbf/ft^2);
R = gas constant, J/kg·K (ft·lbf/lbm·°R); and
T = absolute temperature of exhaust gases, K (°R).

The volumetric flow of exhaust gases in plume is

$$\dot{V} = C_4 \frac{\dot{m}}{\rho_p} \tag{8}$$

where

$\dot{m}$ = mass flow of exhaust air, kg/s (lb/s);
V = volumetric flow of exhaust gases, m^3/s (cfm);
ρ_p = density of exhaust gases, kg/m^3 (lb/ft^3); and
C_4 = 1 (60).

The major assumptions of the above analysis are listed below.

1. The simple plume mass flow equation is appropriate for atria smoke management applications.
2. The heat release rate of the fire is constant.
3. The clear height is greater than the mean flame height.
4. The smoke layer is adiabatic.
5. The plume flow and the exhaust are the only significant mass flows into or out of the smoke layer.

The applicability of simple plume equations has been discussed in part I. Generally smoke layers in atria are not adiabatic, but the adiabatic assumption is both useful and conservative. Without this assumption, the analysis would be complicated by the incorporation of heat transfer. The assumption is conservative in that incorporating heat transfer results in lower volumetric flow rates of exhaust air. Thus assumption 3 may not be true, but it is conservative and results in a simplified analysis. With regard to assumption 4, the potential for leakage from the outside or from other building spaces to the smoke layer should be checked. If such flows exist, the analysis can be modified by increasing the exhaust flow accordingly.

If the smoke layer is not deep enough relative to the exhaust inlets, there is the possibility of pulling some air from below the smoke layer into the exhaust, and this would reduce the effectiveness of the exhaust system. Such reduced effectiveness would result in a smoke layer interface going below the design value and could expose occupants to smoke. Currently, designers use engineering judgment in the selection of this height; however, ASHRAE has an ongoing research project to study this issue.

PRESTRATIFICATION AND DETECTION

Often a hot layer of air forms under the ceiling of an atrium, the result of solar radiation on the atrium roof. While studies have not been made of this *prestratification* layer, building designers indicate that the temperatures of such layers are often in excess of 50°C (120°F). Temperatures below this layer are controlled by the building's heating and cooling system, and the temperature profile can be considered to increase significantly over a small increase in elevation, as shown in Figure 3a. An analysis of smoke stratification is given in NFPA 92B, but it is not appropriate for the temperature profile addressed of this section.[2]

When the average temperature of the plume is less than that of the prestratification layer, the smoke will form a stratified layer under it, as shown in Figure 3b.

Average plume temperatures can be calculated from Equations 7 and 14 of part I, and they are graphed in Figure 4. It can be observed from Figure 4 that the average plume temperature is usually less than the expected temperatures of the hot air layer. Thus when there is a hot prestratified air layer, smoke cannot be expected to reach the ceiling of the atrium, and smoke detectors mounted on that ceiling cannot be expected to go into alarm.

Beam smoke detectors used to detect smoke in the plume can overcome the limitations of ceiling-mounted detectors in atria. Generally the light beams are oriented horizontally. Beam-detectors are often mounted on balconies, where they are generally easier to reach for maintenance than are detectors that are mounted on the ceilings of the atrium. The beams need to be below the prestratified hot layer, and the space between beams needs to be small enough so that plumes will be detected regardless of where the fire is located. As stated in the first paper, the plume diameter equation ($D_p = z/2$) describes the visible plume diameter with an estimated uncertainty in the range of +5% to −40%. Therefore, it is suggested that the spacing between beams be

$$x = \frac{H_b}{4} \tag{9}$$

where

x = minimum spacing between light beams, m (ft);
H_b = height of beams above floor, m (ft).

The height of beams above the floor, H_b, needs to be well below the prestratification layer so that the plume will reach the level of the beams and be detected. Figure 5 is an example arrangement of beam detectors in an atrium.

MAKE-UP AIR

The same mass flow rate of air exhausted from the top of the atrium needs to enter the atrium below the smoke layer. One approach is to introduce this air through openings to the

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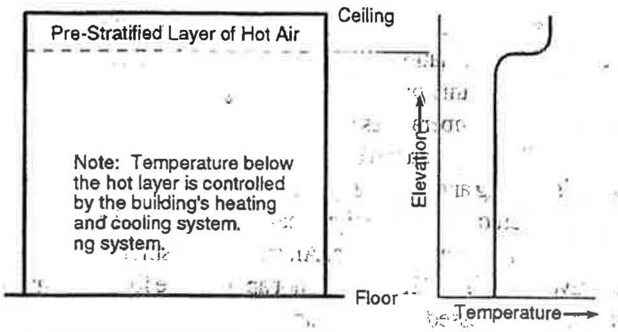
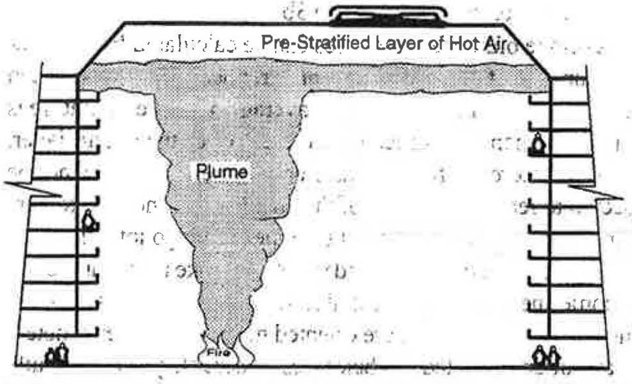
[2] The analysis of smoke stratification in NFPA 92B is for a constant temperature increase per unit elevation (dT/dz = constant). This anlysis does not apply to the prestratification layer that forms under the atrium ceiling. When conditions of constant dT/dz exist in a large space, the NFPA 92B approach can be used to estimate the maximum height of smoke rise.



(a) Pre-stratified layer of hot air under atrium ceiling without a fire



(b) Smoke from a fire filling a pre-stratified atrium

Figure 3. Smoke stratification due to a prestratified hot air layer.

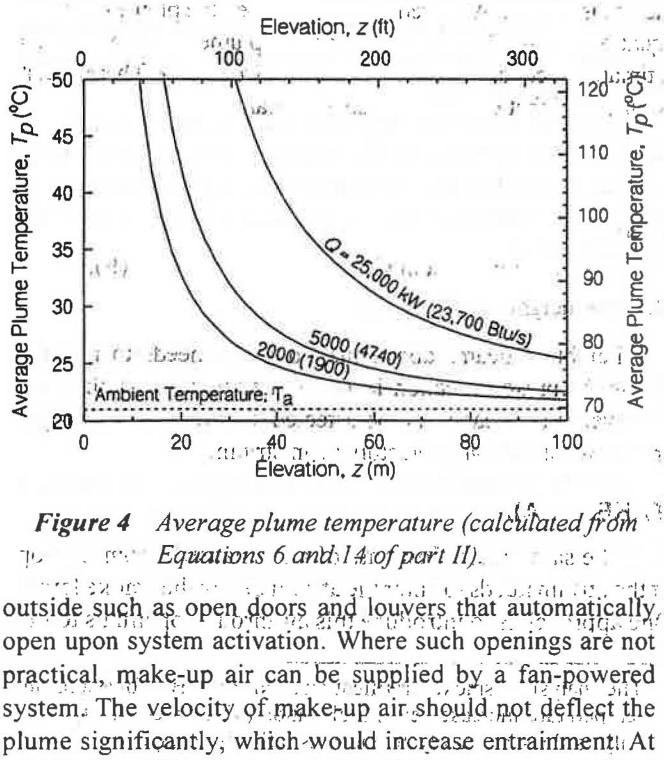


***Figure 4** Average plume temperature (calculated from Equations 6 and 14 of part II).*

outside such as open doors and louvers that automatically open upon system activation. Where such openings are not practical, make-up air can be supplied by a fan-powered system. The velocity of make-up air should not deflect the plume significantly, which would increase entrainment. At locations where the make-up airflow could contact the plume, the velocity of this airflow should not exceed about 1 m/s (200 fpm).

SEPARATED SPACES

Spaces away from the atrium can either be separated from the atrium or they can be open to the atrium. *Separated spaces* are isolated from the atrium by smoke barriers, and these smoke barriers are either vertical or horizontal membranes that are designed and constructed to resist the movement of smoke. Walls, floors, and ceilings can be smoke barriers, and these barriers may have a fire-resistive rating. Smoke barriers may have doorways or other openings that are protected by automatically closing devices such as doors or dampers. Separated spaces can rely on the integrity of the smoke barriers or can also rely on smoke control by pressurization as addressed in NFPA 92A (1993) and Klote and Milke (1992).

COMMUNICATING SPACES

Communicating spaces are spaces within a building that have an open pathway to an atrium. The communicating spaces may open directly into the atrium or they may be connected through an open passage.

Other Plumes

Balcony spill plumes and window plumes are both addressed in NFPA 92B (1991) and by Klote and Milke (1992) as means of smoke flow into the atrium from a fire in a communication space. The method of analysis of these plumes is based on there being hot, buoyant smoke flowing into the atrium. If the fires in the communicating spaces are sprinklered, the resulting smoke is neither hot nor buoyant. Considering that the communicating spaces in most new buildings with atria in the United States are sprinklered, this paper does not address spill plumes or window plumes.

It may be possible to have an atrium building (possibly retrofit) without sprinklers in communicating spaces, and these other plumes should be considered in the analysis of an atrium system.

Airflow for a Communicating Space Fire

Airflow can be used to prevent smoke flowing from a fire in a communicating space to the atrium. The intent of this approach is to protect the atrium and nonfire communicating spaces. The fundamental question concerning this approach is what level of protection is provided. Currently, there is insufficient information to evaluate whether these systems provide any significant level of protection to life or if their sole benefit is property protection.

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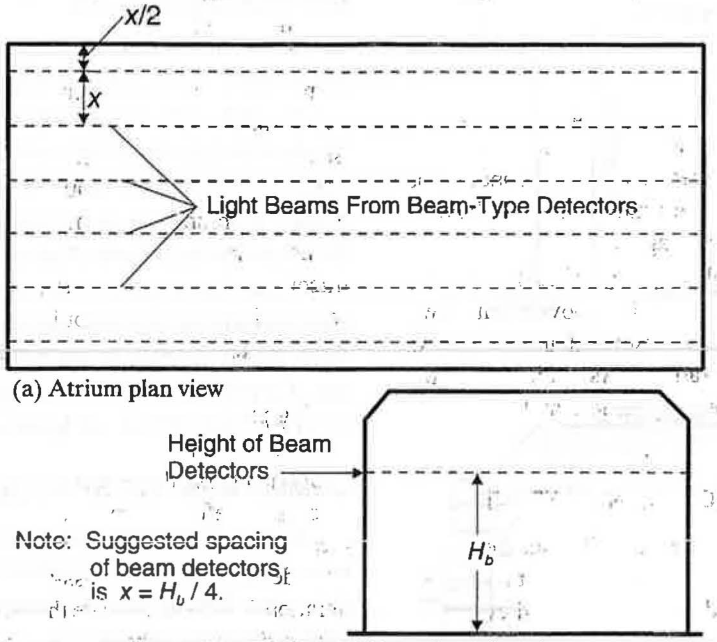
3. Based on fire experiments (Madrzykowski 1991; Lougheed 1997) it would seem that sprinklered fires of office building materials in typical configurations would not result in lethal condition in spaces away from the room of fire origin even for fires that are shielded from the spinkler spray. Further, ASHRAE has a research project to study the hazard to life reulting from sprinklered fires in a communication space.



(a) Atrium plan view

(a) Atrium elevation

Figure 5 *Beam detectors used for activation of atrium smoke management system.*

The issue of evaluation of the potential benefit of this approach is further complicated by the concern about airflow supplying combustion air for a fire. Klote and Milke (1992) address this issue, and they recommend that airflow not be used for smoke control, except when the fire is suppressed or in the rare cases when fuel can be restricted with confidence.

If it is desired to use airflow to prevent smoke originating in the communicating space from flowing into the atrium, the air needs to be exhausted from the communicating space. The exhaust flow rate needs to be sufficient to result in an average air velocity in the opening between the communicating space and the atrium to prevent smoke flow. NFPA 92B (1991) recommends the following equation by Heskestad (1989) for the limiting velocity to prevent smoke backflow:

$$V = C_{13}\sqrt{\frac{gH(T_f - T_o)}{T_f}} \qquad (10)$$

where

V = average air velocity, m/s (ft/min);
g = acceleration of gravity, m/s^2 (ft/s^2);
H = height of opening, m (ft);
T_f = temperature of heated smoke, K (°R);
T_o = temperature of ambient air, K (°R); and
C_{13} = 0.64 (38).

Determination of realistic temperatures of smoke from a sprinklered fire is difficult. Lui (1977) studied the evaporative cooling of sprinkler spray on fire gases and showed that smoke temperatures were sometimes cooled below ambient temperature. NFPA 92B (1991) indicates that 74°C (165°F) is considered realistic for sprinklered fires. In the absence of good data applicable to the above equation, the indicated temperature was the best advice that the NFPA committee responsible for NFPA 92B was able to give on this subject. Before sprinklers take effect, the elevated gas temperature is restricted to a thin layer (0.05 to 0.1 m [2 to 4 in.]) below the ceiling. After sprinklers are activated, this temperature may be conservatively high, considering the findings of Lui.

Research is needed to evaluate the potential benefits of these airflow systems. If the benefits support use of these systems, research is needed to develop an approach that can be applied to sprinklered fires with more confidence than the approach above.

Airflow for an Atrium Fire

Airflow can also be used to prevent smoke flowing from the atrium to the communicating space. The comments from the previous section about the uncertainty of the level of protection provided also apply to the systems of this section.

Air can be supplied to a communicating space to achieve a specific average velocity at the opening to the atrium. This velocity should be such that smoke flow to the communicating space is prevented. For opening locations below the smoke layer and 3 m (10 ft) above the base of the fire, the NFPA 92B (1991) equation for this velocity is

$$V = C_{14}\left(\frac{Q}{z}\right)^{1/3} \qquad (11)$$

where

V = average air velocity, m/s (ft/min);
Q = heat release rate of the fire, kW (Btu/s);

z = distance above the base of the fire to the bottom of the opening, m (ft); and

C_{14} = 0.057 (17).

If the velocity calculated from the above equation is greater than 1 m/s (200 fpm), then a velocity of 1 m/s (200 fpm) should be used. This limitation was made out of concern that greater velocities could disrupt the plume flow and have an adverse effect on atrium smoke management.

For openings above the smoke layer interface, Equation 10 should be used to calculate the velocity. The above equation was provided for NFPA 92B (1991) by Heskestad and is based on unpublished theoretical considerations. As with the section above, research is needed concerning airflow and fires in the atrium.

COMMISSIONING AND ACCEPTANCE TESTING

Commissioning is needed to ensure that smoke control systems will function as intended during fire situations. Many designers and builders have told the author that they believe acceptance testing is the major problem with smoke control systems. They say that everything goes well up to testing, and then the system fails to pass the tests required by the local authority. However, acceptance testing is not the major problem—it is the symptom of the real problems. A commissioning approach can reduce the potential for difficulties during the acceptance test. The guideline for commissioning (ASHRAE 1994) includes the following:

- pre-design phase,
- design phase,
- construction phase,
- acceptance procedures, and
- post-acceptance phase.

The pre-design phase includes identification of objectives and initial development of a commissioning plan. The design phase includes documentation of design criteria, assumptions, description of system, description of required performance, test procedure, project schedule, and system certification. The basic principle behind selection of a test procedure is that the test needs to verify system performance under fire conditions. The construction phase includes review of submittals for equipment and controls, as well as testing, adjusting, and balancing of air-moving systems. Acceptance procedures includes preparation for the test, conducting the test, and documentation of the test results. Post-acceptance efforts include maintenance, any system modifications, and documentation.

Fire Tests

A real fire is the most realistic method of testing a smoke control system. It is an understatement to say that the construction community has concerns about the danger of building fires in atria. The information in this brief section is intended to give the reader an idea of what can be done concerning real fire tests, and readers wishing to conduct such tests should start by making an exhaustive investigation into the topic.

Real fire tests of atria smoke management systems are common in Australia (Atkinson 1992; Atkinson and Marchant 1992), and one such test has been conducted in the United States (Dillon 1994). The Australian tests use ethyl alcohol pool fires of 1,000 to 5,000 kW, and chemical smoke tracer to make the plume and smoke layer visible. Dillon used a propane fire of 5,000 kW with a different chemical smoke tracer. While the propane fire was more expensive, it had the safety advantage that it could be shut off quickly by closing a valve. Determination of the heat release rate is probably made more accurate with the propane by metering the flow and having propane of certified heating value.

Because of concern about heat damage to ceiling and structural members, the centerline plume temperature should be calculated before the test. Atkinson and Marchant indicate that these estimates have been wrong on a few occasions, and they provide an alternative mass-weighted calculation that requires iteration. They also indicate that these real fire tests require attention to detail, and they express concern about the danger that could result from badly applied tests.

Performance Tests Without a Fire

Performance tests without a fire consist of measuring the performance of the system components to ensure that these are functioning as intended during system design. For an atrium exhaust system, this would consist of measuring the exhaust flow and any other flows that are part of the design. For a system that has been designed by a professional engineer upon accepted engineering principles (such as those discussed in this paper), these flow measurements are a sufficient indication that the system will perform as desired under fire conditions.

Chemical Smoke Tracer Tests

Chemical smoke from smoke bombs or smoke generators can be used to test for smoke feedback into supply air. The general procedure for testing with chemical smoke is described here. A number of smoke bombs are placed in a metal container, and all bombs are simultaneously ignited. The container is located near an exhaust inlet in the smoke zone being tested so that all of the chemical smoke produced by the bombs is drawn directly into the exhaust airstream. If chemical smoke is detected in the supply air, its path should be determined, the path should be blocked, and then the smoke feedback test should be conducted again.

For pressurization systems located in spaces separated from the atrium, chemical smoke or other tracers can be useful in locating the leakage paths that sometimes defeat a smoke control system. For example, if the construction of a stairwell is unusually leaky, pressurization of that stairwell may not be possible with fans sized for construction of average tightness. Chemical smoke generated within the stairwell will flow through the leakage paths and indicate their location so that they can be caulked or sealed.

Caution About Chemical Smoke

Caution needs to be given concerning the use of chemical smoke. In the absence of a real fire, this chemical smoke has little or no buoyancy. Chemical smoke does not move like hot smoke from a flaming fire. The unrealistic nature of smoke tests from smoke bombs was illustrated by the experiments at the Plaza Hotel (Klote 1990).

Because chemical smoke tests do not test the system with a realistic fire plume, the test results cannot determine system performance against real fire conditions. It is possible that a system that would fail a chemical smoke test could perform as intended during a fire. Conversely, a system that passed a chemical smoke test could fail to perform during a fire. A serious concern with smoke bomb tests is that they can give building occupants and fire service officials a false sense of security.

SUMMARY AND CONCLUSIONS

1. The approach of atrium exhausting presented in this paper and in NFPA 92B (1991) is based on the fundamentals of plume mechanics, and designers can have a level of confidence in systems designed to these principles. As with all systems, designers need to exercise care that they are within the limitations of the technology, and design fires must be large enough to realistically reflect the high probability of transient fuels.
2. Exhaust is not necessary for an atrium of sufficient filling capacity such that occupants have time for both decision making and evacuation before the smoke fills to where they are located. Approaches to atrium filling can be used to obtain a conservative estimate of filling time. These calculations can be done by computer zone fire models.
3. For situations where the basic methods above are not applicable, physical modeling and CFD analysis can be used for design. The basic approaches are not applicable when the design exceeds the range of applicability of the equations or when obstructions in an atrium do not allow plume flow.
4. Often a hot layer of air forms under the ceiling of an atrium, and this hot layer can prevent smoke from reaching the ceiling. Therefore, ceiling-mounted smoke detectors are generally not recommended for atrium applications. Beam smoke detectors used to detect smoke in the plume as described in the text are recommended.
5. Commissioning is needed to ensure that smoke control systems will function as intended during fire situations. Commissioning efforts should start before design and extend to maintenance system modifications after construction is finished.
6. There is concern about exhaust effectiveness for relatively thin smoke layers. There is the possibility of pulling some air from below the smoke layer into the exhaust, and this could expose occupants to smoke. Such reduced effectiveness would result in a smoke layer interface going below the design value and could expose occupants to smoke. Research is needed concerning the depth of the smoke layer required to prevent atrium exhaust from pulling air from the lower layer.
7. Research is needed concerning use of airflow for smoke control between the atrium and communicating spaces. Information is needed to evaluate the potential benefits of these airflow systems. If the benefits support use of these systems, research is needed to develop new approaches for sprinklered fires.

NOMENCLATURE

A = cross-sectional area of the atrium
C = constant
C_p = specific heat of plume gases
D_p = diameter of visible plume
g = acceleration of gravity
H = height of opening or of ceiling above the floor
H_b = height of beams above floor
h_e = enthalpy of flow leaving the control volume
h_i = enthalpy of flow entering the control volume
$\dot{m}$ = mass flow rate
p = absolute pressure
Q = heat release rate
Q_c = convective heat release rate
R = gas constant
t = time
T = temperature
T_a = ambient temperature
T_f = temperature of heated smoke
t_g = growth time
T_o = temperature of ambient air
T_p = adiabatic exhaust temperature or average plume temperature at elevation z
V = average air velocity
$\dot{V}$ = volumetric smoke flow at elevation
x = minimum spacing between light beams
z = clear height above top of fuel or height of the first indication of smoke above the fire
ρ = density

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