Prediction of Smoke Movement in Atria: Part I—Physical Concepts

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ABSTRACT

In recent years, the atrium building has become commonplace. This paper explains the physical concepts of the steady fire, unsteady fire, zone fire model, and the fire plume that are the basis of atrium smoke management. The approach to smoke control design calculation in codes is based on the zone fire model concept. In the zone model, smoke forms an upward-flowing fire plume that reaches the ceiling and is considered to form a perfectly mixed layer under the ceiling of the room of fire origin. This paper shows that the commonly used virtual origin correction to the plume equations is not needed for atria smoke management. For the purposes of smoke management, the deviations of fire plume mass flow due to omitting the virtual origin correction can be neglected.

INTRODUCTION

In recent years, the atrium building has become commonplace. Other large open spaces include enclosed shopping malls, arcades, sports arenas, exhibition halls, and airplane hangars. The methods of this paper also apply to these spaces. For simplicity, the term "atrium" is used in this paper in a generic sense to mean any of these large spaces. The traditional approach to fire protection by compartmentation is not applicable to these large-volume spaces.

The ability of sprinklers to suppress fires in spaces with ceilings higher than 11 to 15 m (35 to 50 ft) is limited (Degenkolb 1975, 1983). Because the temperature of smoke decreases as it rises (due to entrainment of ambient air), smoke may not be hot enough to activate sprinklers mounted under the ceiling of an atrium. Even if such sprinklers activate, the delay can allow fire growth to an extent beyond the suppression ability of ordinary sprinklers. Some studies have been done concerning prediction of smoke movement and temperature in tall spaces (Notarianni and Davis 1993; Walton and Notarianni 1993). Considering the limitations of compartmentation and sprinklers for atria, it is not surprising that the fire protection community is concerned about atrium smoke management.

This paper explains the physical concepts of the steady fire, unsteady fire, zone fire model, and the fire plume that are the basis of atrium smoke management. A second paper presents information intended for atrium smoke management system design applications (Klote 1997). NFPA 92B (1991) and 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.

DESIGN FIRES

The design fire has a major impact on the atrium smoke management system. The fire size is expressed in terms of the rate of heat release. Fire growth is the rate of change of the heat release rate and is sometimes expressed as a growth constant that identifies the time required for the fire to attain a particular rate of heat release. Designs may be based on either steady or unsteady fires.

Steady Fires

It is the nature of fires to be unsteady, but the steady fire is a useful idealization. Steady fires have a constant heat release rate. In many applications, use of a steady design fire leads to straightforward and conservative design.

Morgan (1979) suggests a typical rate of heat release per unit floor area for mercantile occupancies of 500 kW/m^2 (44 Btu/s·ft^2). Fang and Breese (1980) determined about the same rate of heat release for residential occupancies. Morgan and Hansell (1987) and Law (1982) suggest a heat release rate per unit floor area for office buildings of 225 kW/m^2 (20 Btu/s·ft^2).

In many atria, the fuel loading is severely restricted with the intent of restricting fire size. Such atria are characterized by interior finishes of metal, brick, stone, or gypsum board and are

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furnished with objects made of similar materials plus plants. Even for such a *fuel-restricted* atrium, there are many combustible objects that are in the atrium for short periods. Packing materials, Christmas decorations, displays, construction materials, and furniture being moved into another part of the building are a few examples of transient fuels. For this paper, a heat release rate per floor area of 225 kW/m^2 (20 Btu/s·ft^2) will be used for a fuel-restricted atria, and 500 kW/m^2 (44 Btu/s·ft^2) will be used for atria with furniture, wood, or other combustible materials.

Transient fuels must not be overlooked when selecting a design fire. The approach suggested by Klote and Milke (1992) to incorporate transient fuels in a design fire is to consider the fire occurring over 9.3 m^2 (100 ft^2) of floor space. This would result in a design fire of 2,100 kW (2,000 Btu/s) for restricted fuel atria. If a fire occurred over 9.3 m^2 (100 ft^2) of an atria with combustibles, a design fire of 4,600 kW (4,400 Btu/s) would result. However, the area involved in the fire may be much greater, and determination of it involves flame spread considerations (NFPA 1991; Klote and Milke 1992). A large atrium fire of 25,000 kW would involve an area of 50 m^2 (540 ft^2) at 500 kW/m^2 (44 Btu/s·ft^2). For this paper, discussion of steady design fires will be focused on 2,000 kW, 5,000 kW, and 25,000 kW (1,900 Btu/s, 4,700 Btu/s, and 24,000 Btu/s) as listed in Table 1.

TABLE 1
Steady Design Fire Sizes for Atria

	kW	(Btu/s)
Minimum fire for fuel-restricted atrium	2,000	(1,900)
Minimum fire for atrium with combustibles	5,000	(4,700)
Large fire	25,000	(24,000)

Unsteady Fires

Fires frequently proceed through an incubation period of slow and uneven growth followed by a period of established growth, as illustrated in Figure 1a. Figure 1b shows the established growth as often represented by an idealized parabolic equation (Heskestad 1984):

$$Q = a(t - t_o)^2 \tag{1}$$

where

Q = heat release rate of fire, kW (Btu/s);
a = fire growth coefficient, kW/s^2 (Btu/s^3);
t = time after ignition, s;
t_o = effective ignition time, s.

It is generally recognized that consideration of the incubation period is not necessary for design of atrium smoke control systems, and Equation 1 can be expressed as

$$Q = at^2 \tag{2}$$

where t is the time after effective ignition, and fires following Equation 2 are called t-squared fires. NFPA 92B (1991) makes extensive use of the growth time concept, where the growth time, t_g, is the time after effective ignition for the fire to grow to 1,055 kW (1,000 Btu/s). Table 2 lists values of a and t_g for some general fire types, and the corresponding fire growths are shown in Figure 1c.

TABLE 2
Typical Fire Growth Constants

	Growth Constant		Growth Time
T-Squared Fires	a (kW/s^2)	a (Btu/s^3)	t_g (s)
Slow†	0.002931	0.002778	600
Medium†	0.01127	0.01111	300
Fast†	0.04689	0.04444	150
Ultra Fast‡	0.1878	0.1778	75

† Constants for these fire growth types based on data from NFPA 204 (1991) and NFPA 92B (1991).
‡ Constants for the ultra fast fire based on data from Nelson (1987).

Fire growth may be approximated by the t-squared curve for some time. Because of the action of a suppression system, limitations of fuel, or limitations of combustion air, t-squared fire growth eventually must stop. Generally the action of a suppression system results in a decrease in the heat release rate (Madrzykowski 1991). However, limitations of fuel and of combustion air can result in a nearly constant rate of heat release following a t-squared fire growth. Because atria are large spaces, the growth of fires in atria is usually not restricted by lack of combustion air. Figure 1d illustrates t-squared fire growth followed by a constant heat release rate.

ZONE FIRE MODEL CONCEPT

The approach to smoke control design calculation in codes is based on the zone fire model concept. Also, this concept has been applied to several computer models. These computer models include the Harvard Code (Mitler and Emmons 1981), ASET (Cooper 1985), the BRI Model (Tanaka 1983), CCFM (Cooper and Forney 1987), and CFAST (Peacock et al. 1993). A U.S. university has made modifications to CCFM, specifically for atrium smoke management design (Milke and Mower 1994). CFAST has an approach to account for mass being added to the upper layer when the plume temperature is lower than that of the smoke layer. While each of these models has unique features, they all share the same basic two-zone model concept.

This section is an overview of zone fire modeling, but for more information about zone models, readers are referred to Bukowski (1991), Jones (1983), Mitler and Rockett (1986), Mitler (1984), and Quintiere (1989). Zone models have proven utility for many fire protection applications, including hazard analysis (Peacock et al. 1991; Bukowski et al. 1991). The ASET-

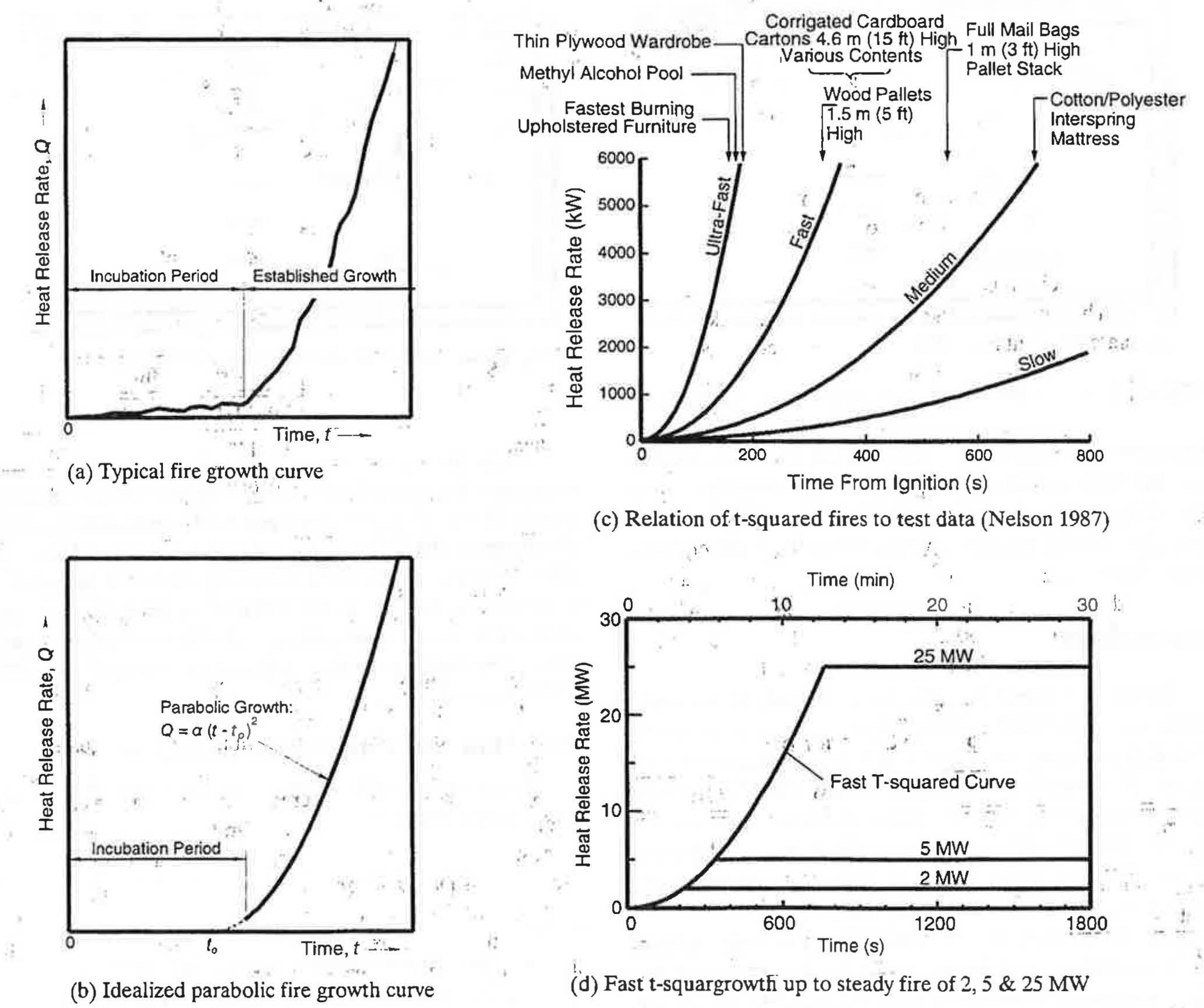


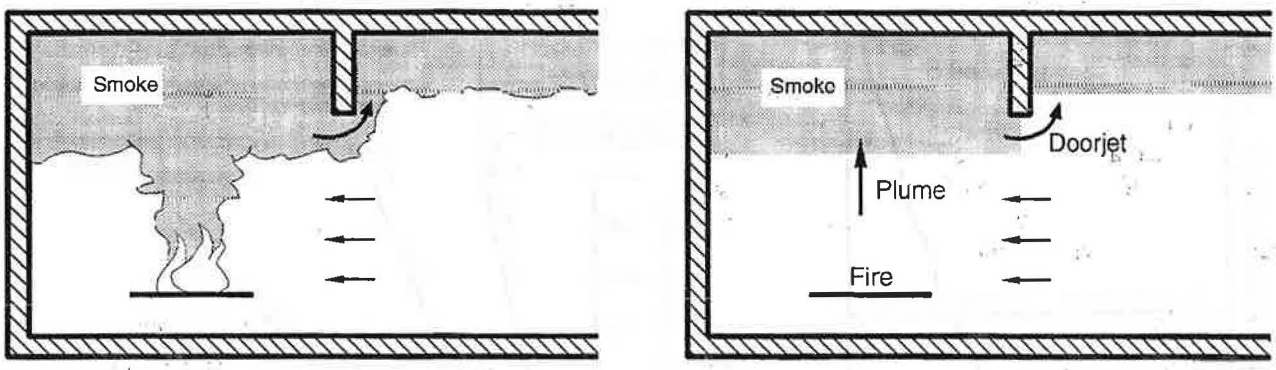
Figure 1 *Various fire growth curves.*

B model (Walton 1985) is a simple model that is a good starting point for people to learn about zone models.

Because zone models were originally developed for room fires, this discussion will start with room fires. In a room fire, hot gases rise above the fire, forming a plume. As the plume rises, it entrains air from the room so that the diameter and mass flow rate of the plume increase with elevation. Accordingly, the plume temperature decreases with elevation. The fire gases from the plume flow up to the ceiling and form a hot stratified layer under the ceiling. The hot gases can flow through openings in walls to other spaces, and such flow is referred to as a "doorjet." The doorjet is similar to a plume in that air is entrained and the mass flow rate and cross-sectional area of the jet increase with elevation, and the jet temperature decreases with elevation. The difference is that the doorjet flows through an opening in a wall. Figure 2a is a sketch of a room fire.

The concept of zone modeling is an idealization of the room fire conditions as illustrated in Figure 2b. For this idealization, the temperature of the hot upper layer of the room is uniform, and the temperature of the lower layer of this room is also uniform. The height of the discontinuity between these layers is the same everywhere. The dynamic effects on pressure are considered negligible, so that the pressures are treated as hydrostatic. Other properties are considered uniform for each layer. Algebraic equations are used to calculate the mass flows due to plumes and doorjets.

Many zone computer models allow exhaust from the upper layer, and this capability is essential for simulation of atrium smoke exhaust systems. Many of the computer zone models esti-



(a) Sketch of a room fire (b) Zone model idealization of a room fire

Figure 2 *Room fire (a) sketch and (b) zone model idealization.*

mate heat transfer by methods ranging from a simple allowance as a fraction of the heat released by the fire to complicated simulation including the effects of conduction, convection, and radiation. Zone model application to an atrium fire is illustrated in Figures 3a and 3b.

FIRE PLUMES

The plumes above fires that are of interest in this paper pulsate and are formed of many eddies. Morton et al. (1956) developed a classic analysis of the time-averaged flow of plumes. They considered the plume to be coming from a point source (or a line source). For a height above the plume source, they considered the air entrained at the plume edge to be proportional to some characteristic velocity of the plume at that height. The variations of density in the plume were considered small compared to ambient density. The profiles of mean vertical velocity and mean buoyancy force in the horizontal sections were considered to be of similar form at all heights. Figure 4a is an illustration of a plume, and Figure 4b is a velocity diagram of an idealized plume model.

The plume of Figure 4 is called an axisymmetric plume, and researchers have extended the work of Morton et al. to develop models of the turbulent plumes due to fires in building spaces (for example McCaffrey 1983; Cetegan et al. 1982; Heskestad 1984). Because Heskestad's plume equation and his related work were the basis of NFPA 92B (1991), these equations are used in this paper. These equations are for steady plumes, and some considerations of steady plumes are discussed by Klote (1994, Appendix H).

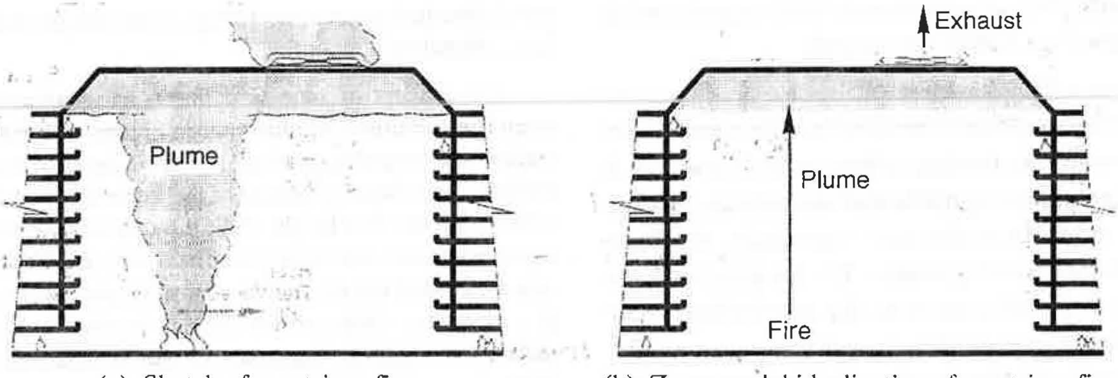
Mass Flow with Virtual Origin Correction

Heskestad's (1984) equation for the mass flow of an axisymmetric plume is

$$\dot{m} = C_1 Q_c^{1/3}(z - z_o)^{5/3}[1 + C_2 Q_c^{2/3}(z - z_o)^{-5/3}] \quad (3)$$

where

$\dot{m}$ = mass flow in plume at height z, kg/s (lb/s);
Q_c = convective heat release rate of fire, kW (Btu/s);
z = height above top of fuel, m (ft);
z_o = virtual origin of the plume, m (ft);



(a) Sketch of an atrium fire (b) Zone model idealization of an atrium fire

Figure 3 *Atrium fire (a) sketch and (b) zone model idealization.*

C_1 = 0.071 (0.022); and

C_2 = 0.026 (0.19).

Because smoke was defined to include the air that is entrained with the products of combustion, all of the mass flow in the plume is defined as being smoke. It follows that Equation 3 can be thought of as an equation for the production of smoke from a fire. A simplified plume mass equation will be presented later, and the same comments also apply to it.

Virtual Origin

Heskestad's (1983) relationship for the virtual origin is

$$z_o = C_3 Q^{2/5} - 1.02 D_f \quad (4)$$

where

Q = heat release of the fire, kW (Btu/s);

D_f = diameter of fire, m (ft); and

C_3 = 0.083 (0.278).

In Figures 4a and 4b the virtual origin is shown above the top of the fuel, but it can also be below the fuel. The sign convention is: for the virtual origin above the top of the fuel z_o is positive, and for the virtual origin below the top of the fuel z_o is negative. The convective portion of the heat release rate, Q_c, can be expressed as

$$Q_c = \xi Q \quad (5)$$

where ξ is the convective fraction of heat release. The convective fraction depends on the heat conduction through the fuel and the radiative heat transfer of the flames, but a value of 0.7 is often used for ξ.

Average Plume Temperature

The average temperature of the plume can be obtained from a first law of thermodynamics analysis of the plume. Consider the plume as a steady flow process with the control volume of Figure 4c. Neglecting the small amount of mass added to the plume flow due to combustion, the first law for the plume is

$$Q_g + Q_t = \dot{m}(h_e - h_i + \Delta KE + \Delta PE) + W \quad (6)$$

where

Q_g = heat generated within the control volume, kW (Btu/s);

Q_t = heat transferred from surroundings into the control volume, kW (Btu/s);

$\dot{m}$ = mass flow rate, kg/s (lb/s);

h_i = enthalpy of flow entering the control volume, kW/kg (Btu/s·lb);

h_e = enthalpy of flow leaving the control volume, kW/kg (Btu/s·lb);

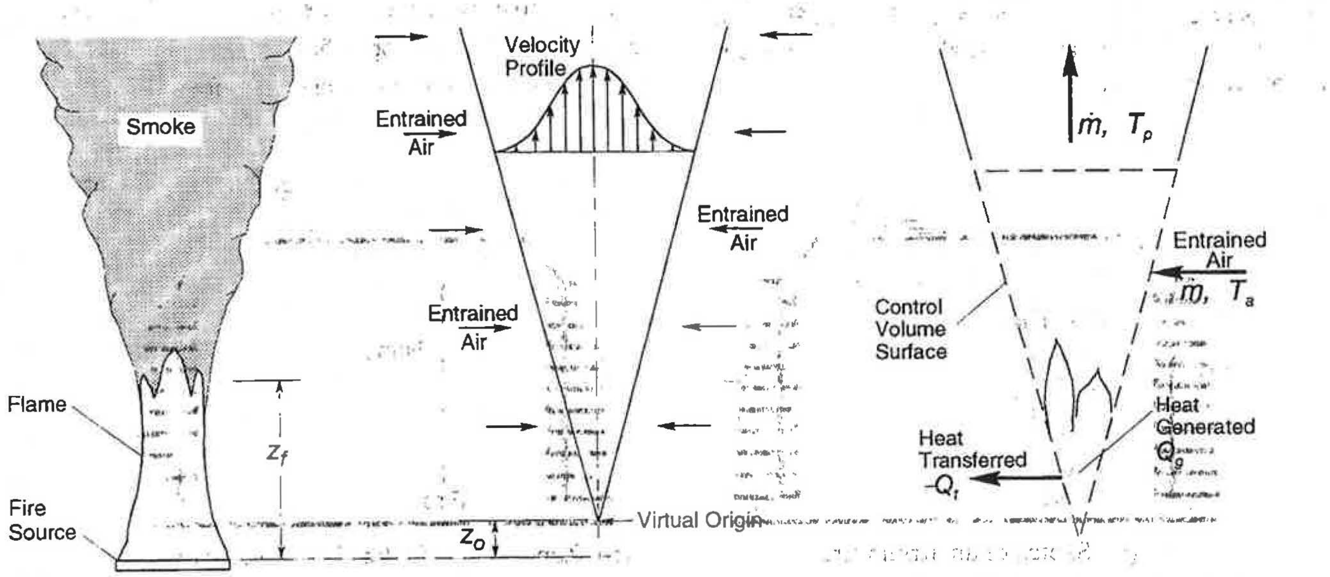
ΔKE = change in kinetic energy, kW/kg (Btu/s·lb);

ΔPE = change in potential energy, kW/kg (Btu/s·lb);

W = work done by system on its surroundings, kW (Btu/s).

For the steady plume the work is zero, and the changes in kinetic and potential energy are negligible. The heat generated is the heat release of the fire ($Q_g = Q$). Heat is transferred from the plume by conduction and radiation to the surroundings, so that $Q_c = Q_g + Q_t$. Specific heat can be considered constant ($h = C_p T$). The first law leads to an equation for the plume temperature:

$$T_p = T_a + \frac{Q_c}{\dot{m} C_p} \quad (7)$$



(a) Sketch of plume (b) Velocity diagram of idealized plume (c) Control Volume diagram of idealized plume

Figure 4 *Axisymmetric fire plume with point source.*

where

T_p = average plume temperature at elevation z, °C (°F);

T_a = ambient temperature, °C (°F);

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

Fire plumes consist primarily of air mixed with the products of combustion, and the specific heat of plume gases is generally taken to be the same as air (C_p = 1.00 kJ/kg·°C [0.24 Btu/lb·°F]). The plume mass flow equation (Equation 3) was developed for strongly buoyant plumes. For small temperature differences between the plume and ambient, errors due to low buoyancy could be significant. This topic needs study, and, in the absence of better data, it is recommended that the plume equations not be used when this temperature difference is small (less than 2°C [4°F]).

Volumetric Flow

The volumetric flow of a plume is

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

where

$\dot{m}$ = mass flow in plume at height z, kg/s (lb/s);

$\dot{V}$ = volumetric smoke flow at elevation z, m³/s (cfm);

ρ_p = density of plume gases at elevation z, kg/m³ (lb/ft³);

C_4 = 1 (60).

Plume Centerline Temperature

The temperature from Equation 7 is a mass flow average, and the temperature varies over the plume cross section. The plume temperature is greatest at the centerline of the plume, and the centerline temperature is of interest when atria are tested by real fires as discussed in the companion paper. The centerline temperature equation (Heskestad 1986) is

$$T_{cp} = T_a + C_5 \left(\frac{T_a}{g C_p^2 \rho_a^2} \right)^{1/3} \frac{Q_c^{2/3}}{(z - z_o)^{5/3}} \tag{9}$$

where

T_{cp} = absolute centerline plume temperature at elevation z, K (°R);

T_a = absolute ambient temperature, K (°R);

ρ_a = density of ambient air, kg/m³ (lb/ft³);

g = acceleration of gravity, m/s² (ft/s²); and

C_5 = 9.1 (0.0067).

For the following conditions of 294 K (529°R), ρ_a of 1.2 kg/m³ (0.075 lb/ft³), g of 9.8 m/s² (32.2 ft/s²), and C_p of 1.00 kJ/kg·°C (0.24 Btu/lb·°F), the centerline temperature equation becomes

$$T_{cp} = T_a + C_6 \frac{Q_c^{2/3}}{(z - z_o)^{5/3}} \tag{10}$$

where

T_p = centerline plume temperature at elevation z, °C (°F);

T_a = ambient temperature, °C (°F); and

C_6 = 25 (338).

Air and Plume Gas Density

The density of air and plume gases is calculated from the perfect gas law:

$$\rho = \frac{p}{RT} \tag{11}$$

where

ρ = density of air or plume gases, kg/m³ (lbm/ft³);

p = absolute pressure, Pa (lbf/ft²);

R = gas constant, J/kg·K (ft·lbf/lbm·°R); and

T = absolute temperature, K (°R).

The absolute pressure is often taken to be standard atmospheric pressure of 101,325 Pa (2,116 lbf/ft²), and the gas constant is generally taken to be that of air, which is 287 J/kg·K (53.3 ft lbf/lbm·°R).

Plume Diameter

The diameter of a plume is approximately

$$D_p = \frac{z}{2} \tag{12}$$

where

D_p = diameter of visible plume, m (ft);

z = height above top of fuel, m (ft).

This equation is within 5% of a more complicated one that is in terms of the plume centerline temperature (NFPA 1991; Klote and Milke 1992). Equation 12 is probably of sufficient accuracy for design applications, considering that plumes are in constant motion and measurement of diameter can only be approximate. Further, the visibility of smoke from different fuels varies considerably, and Equation 12 may be thought of as an indication of an upper value of likely plume diameter. Considering plume diameters can vary significantly from the estimates, plume diameter estimates need to be applied conservatively. The author suggests considering plume diameter estimates to have an uncertainty in the range of plus 5% to minus 40% until better data are available.

Equation 12 can be used to determine if geometry of a specific space lends itself to the smoke management approaches of the paper. The concern is that a plume will contact the walls of the space and fill the cross section of the space with smoke. From Equation 12, it can be said that the atrium smoke management concepts of this paper are not appropriate for spaces that are taller than twice their minimum width.

Flame Height

Equation 3 is applicable for elevations, z, that are above the mean flame height of the fire. The flame height depends on the fire geometry, the ambient conditions, the heat of combustion, and the stoichiometric ratio. A relationship (Heskestad 1988) for flame height that can be used for many fuels is

$$z_f = C_7 Q^{2/5} - 1.02 D_f \tag{13}$$

where

z_f = mean flame height, m (ft);

C_7 = 0.235 (0.788).

The ceiling heights of atria are relatively high, and it is the nature of atria smoke management that the elevations, z, of interest are much greater than either virtual origin, z_0, or the flame height, z_f.

Simple Mass Flow and Flame Height Equations

If the virtual origin correction is negligible, Equation 3 becomes

$$\dot{m} = C_1 Q_c^{1/3} z^{5/3} + C_8 Q_c \tag{14}$$

where

C_1 = 0.071 (0.022) and

C_8 = 0.0018 (0.0042).

This is the *simple plume equation* presented in NFPA 92B (1991). In addition to not needing to calculate z_o, the user of this equation does not need to know D_f. In design applications where the fuel is unknown, these advantages are significant. A corresponding approximate relationship for mean flame height is

$$z_f = C_9 Q_c^{2/5} \tag{15}$$

where

z_f = mean flame height, m (ft);

C_9 = 0.166 (0.533).

DISCUSSION OF SIMPLE EQUATIONS

To evaluate the extent to which the simple equations from the section above are applicable, the fire diameter needs to be addressed. For fires that are not round, the effective diameter is defined as $D_f = 2(A/\pi)^{1/2}$, where A is the area of the fire. The heat release density of a fire is $q = Q/A$. Thus the effective diameter of a fire can be expressed as

$$D_f = 2\sqrt{\frac{Q}{\pi q}} \tag{16}$$

Table 3 lists heat release densities for some warehouse materials (NFPA 1991) and pool fires (Heskestad 1983). In this table q ranges from 90 kW/m^2 (8 Btu/s·ft^2) to 14,000 kW/m^2 (1,250 Btu/s·ft^2). The low value is for a proprietary silicone transformer fluid, and the upper value is for polystyrene jars in compartmented cartons stacked 4.57 m (15 ft) high. These extreme fuel arrangements are not likely to be found in atria, and eliminating them results in a range of 400 kW/m^2 (35 Btu/s·ft^2) to 10,000 kW/m^2 (900 Btu/s·ft^2).

Figure 5a shows the effect of heat release density, q, on the location of the virtual origin. For 400 kW/m^2 (35 Btu/s·ft^2), z_o is about −0.8 m (−2.6 ft) at Q of 2,000 kW and −4.3 m (−14 ft) at Q of 25,000 kW. The negative values of z_o indicated that the virtual origin is below the fire surface. For 10,000 kW/m^2 (880 Btu/s·ft^2), z_o is about 1.2 m (3.9 ft) at Q of 2,000 kW (1,900 Btu/s) and 3 m (10 ft) at Q of 25,000 kW (23,700 Btu/s).

Figure 5b shows the impact of the virtual origin correction on plume mass flow for q = 400 kW/m^2 (35 Btu/s·ft^2), and Figure 5c shows the corresponding impact for q = 10,000 kW/m^2 (880 Btu/s·ft^2). Figure 5b shows that Equation 14 results in underprediction for the lower heat release density, and Figure 5c shows that Equation 14 results in overprediction for the higher heat release density. These over- and underpredictions are with reference to Equation 3. Table 4 lists deviations of mass flow due to omitting the correction. For a 20m (67 ft) atrium, these deviations range from −26% to 26%. For taller atria, the range decreases: at 40 m (130 ft) it is −15% to 13%, and at 80 m (260 ft) it is −8% to 6%. Equation 14 predicts mass flows that are about in the middle of the range of values from Equation 3.

An estimate of the uncertainty of Equation 3 is not available, but it should be noted that the state of plume technology is such that the above ranges may be within the uncertainty of Equation 3. Further, fire spread by radiation can result in a number of nearby fires with separate plumes joining together as they rise. Theories have yet to be developed for such multiple fire plumes. There is no question that both Equations 3 and 14 reflect the important trends of mass flow being a strong function of elevation, z, and a weak function of convective heat release rate, Q_c. However, to conservatively apply Equation 14, it is suggested that the location of the fire surface be conservatively selected. For example, if fires may be possible anywhere from the floor level to 3 m (10 ft) above the floor, conservative selection of fire surface would be at the floor.

Figure 5d compares the predicted flame heights from Equation 13 with the approximate relation of Equation 15. Again, the approximate relation is in the middle of the range of predicted values. It is apparent that flame height, z_f, increases with q. In atria smoke management design, flame height is primarily used to ensure that the plume mass flow equations are appropriate. The flame height, z_f, ranges from 2.4 m (8 ft) to 4.4 m (14 ft) at 2,000 kW (1,900 Btu/s) and from 4.3 m (14 ft) to 12 m (39 ft) at 25,000 kW (23,700 Btu/s).

SUMMARY AND CONCLUSIONS

1. Design fires for atrium smoke management can be steady or unsteady. The t-squared fire growth curve is extensively used in NFPA 92B (1991).
2. The approach to smoke control design calculation in codes is based on the zone-fire model concept. In the zone model, smoke from a fire is considered to form a perfectly mixed

TABLE 3
Heat Release Density of Some Materials

	Heat Release Density, q	
Material Burned	kW/m²	Btu/s ft²
1. Wood pallets, stacked 0.46 m (1.5 ft) high (6-12% moisture)	1400	125
2. Wood pallets, stacked 1.52 m (5 ft) high (6-12% moisture)	4,000	350
3. Wood pallets, stacked 3.05 m (10 ft) high (6-12% moisture)	6,800	600
4. Wood pallets, stacked 4.88 m (16 ft) high (6-12% moisture)	10,000	900
5. Mail bags, filled, stored 1.52 m (5 ft) high	400	35
6. Cartons, compartmented, stacked 4.57 m (15 ft) high	1,700	150
7. PE letter trays, filled, stacked 1.52 m (5 ft) high on cart	8,500	750
8. PE trash barrels in cartons, stacked 4.57 m (15 ft) high	2,000	175
9. PE fiberglass shower stalls in cartons, stacked 4.57 m (15 ft) high	1,400	125
10. PE bottles packed in item 6	6,200	550
11. PE bottles in cartons, stacked 4.57 m (15 ft) high	2,000	175
12. PU insulation board, rigid foam, stacked 4.57 m (15 ft) high	1,900	170
13. PS jars packed in item 6	14,000	1,250
14. PS tubes nested in cartons, stacked 4.27 m (14 ft) high	5,400	475
15. PS toy parts in cartons, stacked 4.57 m (15 ft) high	2,000	180
16. PS insulation board, rigid foam, stacked 4.27 m (14 ft) high	3,300	290
17. PVC bottles packed in item 6	3,400	300
18. PP tubes packed in item 6	4,400	390
19. PP and PE film in rolls, stacked 4.27 m (14 ft) high	6,200	550
20. Methanol pool, 0.16 m (0.52 ft) diameter	2,000	180
21. Methanol pool, 1.22 m (4.0 ft) diameter	400	35
22. Methanol pool, 1.74 m (5.7 ft) diameter	400	35
23. Methanol pool, 2.44 m (8.0 ft) diameter	420	37
24. Methanol pool, 0.97 m (3.2 ft) square	745	66
25. Silicone transformer fluid pool, 1.74 m (5.7 ft) diameter	90	8
26. Silicone transformer fluid pool, 2.44 m (8.0 ft) diameter	90	8
27. Hydrocarbon transformer fluid pool, 1.22 m (4.0 ft) diameter	940	83
28. Hydrocarbon transformer fluid pool, 1.74 m (5.7 ft) diameter	900	80
29. Heptane pool, 1.22 (4 ft) diameter	3,000	270
30. Heptane pool, 1.74 (5.7 ft) diameter	3,200	280

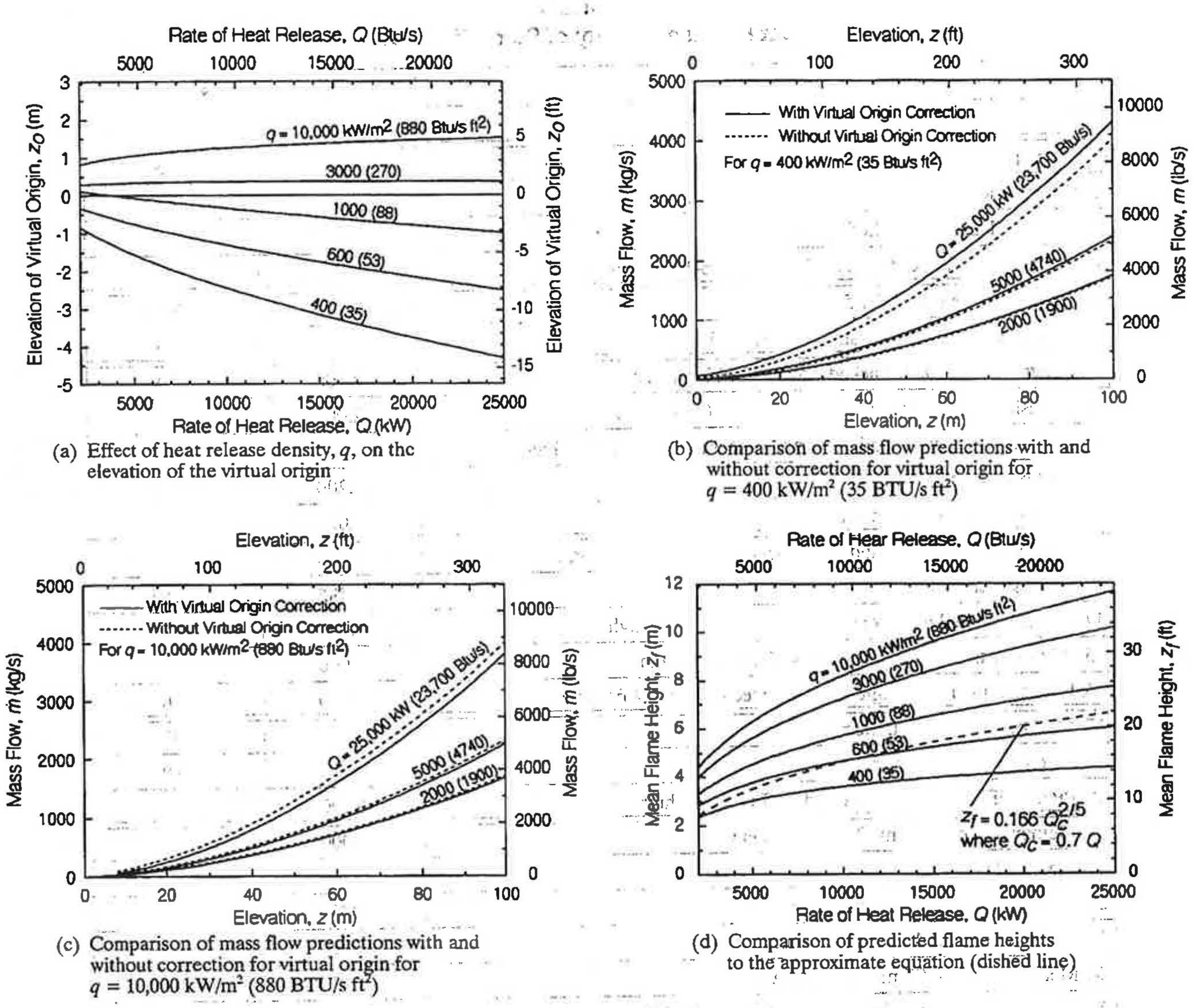
Notes:
1. Abbreviations are: PE = polyethylene, PS = polystyrene, PVC = polyvinyl chloride, PP = polypropylene, PU = polyurethane.
2. Items 1 through 19 from NFPA 92B (1991).
3. Items 20 through 30 from Heskestad (1983).
4. Items 25 through 28 are proprietary products.

layer under the ceiling of the room of fire origin. Smoke production depends on the heat release rate of the fire and on the height of the fire plume.

3. The commonly used virtual origin correction to the plume equations are not needed for atria smoke management. For the purposes of smoke management, the deviations of fire plume mass flow due to omitting the virtual origin correction can be neglected.

NOMENCLATURE

a = fire growth coefficient
A = cross-sectional area of the atrium or area of a fire
C = constant
C_p = specific heat of plume gases
D_f = diameter of fire
D_p = diameter of visible plume



(a) Effect of heat release density, q, on the elevation of the virtual origin

(b) Comparison of mass flow predictions with and without correction for virtual origin for $q = 400$ kW/m² (35 BTU/s ft²)

(c) Comparison of mass flow predictions with and without correction for virtual origin for $q = 10{,}000$ kW/m² (880 BTU/s ft²)

(d) Comparison of predicted flame heights to the approximate equation (dished line)

Figure 5 *Comparison of analysis with and without virtual origin correction.*

TABLE 4
Deviations of Mass Flow Due to Omitting the Virtual Origin Correction

Heat Release Rate, Q		Heat Release Density, q		Elevation above the fire, z		
kW	**Btu/s**	**kW/m²**	**Btu/s ft²**	**20 m (67 ft)**	**40 m (130 ft)**	**80 m (260 ft)**
2,000	1,900	400	35	−7%	−3%	−2%
5,000	4,740	400	35	−11%	−6%	−3%
25,000	23,700	400	35	−26%	−15%	−8%
2,000	1,900	10,000	880	10%	5%	3%
5,000	4,740	10,000	880	15%	7%	4%
25,000	23,700	10,000	880	26%	13%	6%

g = acceleration of gravity
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
Q_g = heat generated within the control volume
Q_t = heat transferred from surroundings into the control volume
q = heat release density of a fire
R = gas constant
t = time
T = temperature
T_a = ambient temperature
T_{cp} = centerline plume temperature
t_g = growth time
t_o = effective ignition time
T_o = temperature of ambient air
T_p = adiabatic exhaust temperature or average plume temperature at elevation z
$\dot{V}$ = volumetric smoke flow at elevation
W = work done by system on its surroundings
z = clear height above top of fuel or height of the first indication of smoke above the fire
z_f = mean flame height
z_o = virtual origin of the plume
ΔKE = change in kinetic energy
ΔPE = change in potential energy
ξ = convective fraction of heat release
ρ = density
ρ_a = density of ambient air
ρ_p = density of plume gases at elevation z or density of exhaust gases

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