PDHonline Course M148 (3 PDH)

Smoke Movement in Buildings

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2012

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SMOKE MOVEMENT IN BUILDINGS

by

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SMOKE MOVEMENT IN BUILDINGS

Revised by John H. Klote and Harold E. "Bud" Nelson

Smoke and fire gases, inherent in all unwanted fires, are dangerous products of combustion that have critical influences on life safety, property protection, and fire suppression practices in buildings. In some fires, the volume of smoke is so great that it may fill an entire building and obscure visibility at the street level to such an extent that it is difficult to identify the fire-involved building. In other incidents, the volume of smoke generated may be considerably less, although the danger to life is not necessarily diminished because of the presence of other airborne products of combustion.

This chapter gives information on the techniques used to evaluate the physical characteristics of smoke movement through both short and tall buildings as a basis for designing smoke-control systems. It also covers the approaches that can be used to test the effectiveness of designed smoke-control systems in the absence of actual performance tests involving test fires.

For more information on controlling the hazards of smoke, see the following chapters in this section: Chapter 7, "Venting Practices," and Chapter 14, "Airconditioning and Ventilating Systems." Also see Section 11, Chapter 10, "Simplified Fire Growth Calculations."

This chapter provides general background, a discussion of relationships, and selected equations useful in understanding smoke movement and smoke management in buildings. Of necessity, the information is not sufficient for detailed design analysis, but design information is available from a number of sources. The 1992 book by Klote and Milke,[1] *Design of Smoke Management Systems*, provides a consolidation and systematic presentation of data and calculations necessary for the design of systems to manage smoke movement. Specific design information is provided in that publication for pressurized stairwells, pressurized elevators, zoned smoke control, and smoke management in large spaces including atria and shopping malls. The smoke-control chapter of the 1995 *SFPE Handbook of Fire Protection Engineering*[2] summarizes much of the general information from Klote and Milke. NFPA 92A, *Recommended Practice for Smoke-Control Systems* (hereinafter referred to as NFPA 92A), was first published in 1988 and provides additional recommendations for stairwell pressurization systems and zoned smoke-control systems, including suggested levels of pressurization for such systems in sprinklered and unsprinklered buildings. NFPA 92B, *Guide for Smoke Management Systems in Malls, Atria, and Large Areas* (hereinafter referred to as NFPA 92B), was first published in 1991, and is a technical guide for the design of smoke management systems in shopping malls, atria, and other large-volume spaces.

CLASSIFICATION OF SMOKE ZONES

As a fire burns, it:

1. Generates heat.
2. Changes major portions of the burning material or fuel from its original chemical composition to one or more other compounds, such as carbon dioxide, carbon monoxide, water, and/or other compounds.
3. Often, due to less than 100 percent combustion efficiency, transports a portion of the fuel as soot or other material that may or may not have undergone a chemical change.

A major portion of the heat generated as a fuel burns remains in the mass of products liberated by the fire. This mass expands, is lighter than the surrounding air, and rises as a plume. The rising plume is turbulent and, because of this, entrains large quantities of air from the surrounding atmosphere into the rising gases. This entrainment:

1. Increases the total mass and volume of the plume.
2. Cools the plume by mixing the cool entrained air with the rising hot gases. Normally, the rising plume is hotter at its center and cooler toward the edges where cooler air is entrained.
3. Dilutes the concentration of fire products in the plume.

Smoke, as discussed in this chapter, is therefore defined as a mixture of hot vapors and gases produced by the combustion process along with unburned decomposition and condensation matter and the quantity of air that is entrained or otherwise mixed into the mass.

For the purposes of describing smoke movement in buildings, the treatment of smoke movement is divided into two general areas: (1) the hot smoke zone and (2) the cool smoke zone.

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Hot Smoke Zone

This zone includes those areas in a building where the temperature of the smoke is high enough so that the natural buoyancy of the body of smoke tends to lift the smoke toward the ceiling while clean, or at least less polluted, air is drawn in through the lower portion of the space. Normally, this condition exists in the room of fire origin. Depending upon the level of energy produced by the fire and the size of connecting openings, such as open doors, hot smoke zones can readily exist in adjacent rooms or corridors. Industrial and warehouse smoke and heat venting, atria smoke removal, and the movement of smoke in corridors open to spaces that have flashed over, all involve a hot smoke zone where the smoke is lifted and driven by the buoyant forces produced by the fire.

Cool Smoke Zone

This zone includes those areas in a building where mixing and other forms of heat transfer have reduced the effect of the driving force of the fire to the point at which buoyant lift in the smoke body is a minor factor. In these areas, the movement of smoke is primarily controlled by other forces, such as wind and stack effects, and the mechanical heat, ventilating, air conditioning, or other air-movement systems. In these areas, the movement of smoke is essentially the same as the movement of any other pollutant.

SMOKE MOVEMENT IN THE HOT SMOKE ZONE

The volume of combustion products entrained in a rising plume in the hot smoke zone is relatively small, compared with the volume of air in the total mixture. Consequently, the smoke produced by a fire will approximate the volume of air drawn into the rising plume. Figure 7-6A illustrates the process.

In situations in which the height of the plume, as measured from the top of the fire to the level of the smoke layer, is more than about twice the height of the solid body of flame, it is reasonable to estimate the amount of smoke using developed formulas.[3,4]

In general, the equations given in this chapter for conditions in the hot smoke zone should be used where the fire is small compared to the height of the space involved. For locations where this is not true, approaches such as those contained in Section 7, Chapter 7, "Venting Practices"; Section 11, Chapter 5, "Deterministic Computer Fire Models"; and Section 11, Chapter 10, "Simplified Fire Growth Calculations" are more appropriate.

The following equation is based on research conducted at Factory Mutual Research Corporation (FMRC) and is the equation used for smoke production in NFPA 92B. The amount of smoke generated can be estimated as

$$\dot{m} = 0.071K^{2/3}Q^{1/3}Z^{5/3} + 0.0018Q_c$$

where

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

Q_c = convective heat release rate of fire, kW;

z = height above top of fuel, m; and

k = wall factor (see Figure 7-6B).

The above equation is the same as the corresponding equation in NFPA 92B for the value of $k = 1$.

The expression also includes a series of assumptions, the most important of which are:

1. The tip of the flame is a significant distance below the bottom of the smoke layer. The formula, while useful, is much less accurate in spaces with a low ceiling relative to the height of the fire involved.
2. The fire bed itself covers an area whose length and width are reasonably approximate to each other. The original formula is based on the assumption of a circular fire. The degree of error in the formula increases as the relationship of length to width increases.
3. The ceiling is sufficiently high so that a correction for the virtual origin of the fire is unnecessary. This is true where the fire is small compared to the height of the space involved, as is the case for small fires in rooms or for design applications involving atria or other large-volume spaces.

Flame Height

A reasonable estimate of the visible flame height[5] can be obtained from the expression:

$$z_f = 0.166(Q/k)^{0.4}$$

where

z_f = mean flame height, m;

Q = heat release of the fire, kW; and

k = wall factor (see Figure 7-6B).

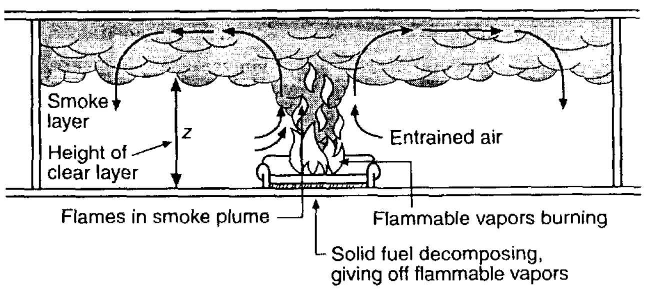

FIG. 7-6A. The production of smoke from a fire.

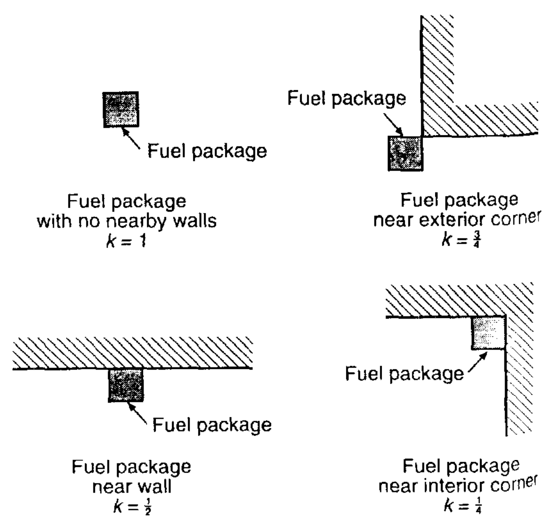

FIG. 7-6B. Wall factors for fuel package locations.

The above equation is the same as the corresponding equation in NFPA 92B for the value of $k = 1$. The convective portion of the heat release, rate, Q_c, can be expressed as

$$Q_c = \xi Q$$

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. The results of this equation for a convective fraction of 0.7 are shown graphically in Figure 7-6C.

Average Plume Temperature

Detailed engineering equations for fire plumes have been presented.[6] However, the average temperature of a fire plume is

$$\Delta T = \frac{Q_c}{\dot{m} C_p}$$

where

ΔT = average temperature increase above room temperature, °C;

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

Q_c = convective heat release rate of fire, kW; and

C_p = specific heat of plume gases, 1.00 kJ/kg °C.

The average temperature difference should not be confused with the centerline plume temperature, which is hotter. The mass flow can be estimated by the plume equations already presented. These plume equations are for strongly buoyant plumes. For small increases over room temperature, errors due to low buoyancy could be significant. This topic needs further study, and, in the absence of better data, it is recommended that the plume equations not be used when the average temperature increase is small [less than 4°F (2°C)]. The average temperature rise of a plume for a fuel package with no nearby walls is shown in Figue 7-D.

Volumetric Plume Flow

The volumetric flow rate of a plume is

$$V = \frac{\dot{m}(T_p + 273)}{353}$$

where

V = volumetric flow rate of plume at height z, m³/s;

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

T_p = average temperature of plume gases at height z, °C.

$$T_p = \Delta T + \text{room temperature}$$

In custom units, this equation is

$$v = 1.51\dot{m}(T_p + 460)$$

where

V = volumetric flow rate of plume at height z, cu ft/min;

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

T_p = average temperature of plume gases at height z, °F.

$$T_p = \Delta T + \text{room temperature}$$

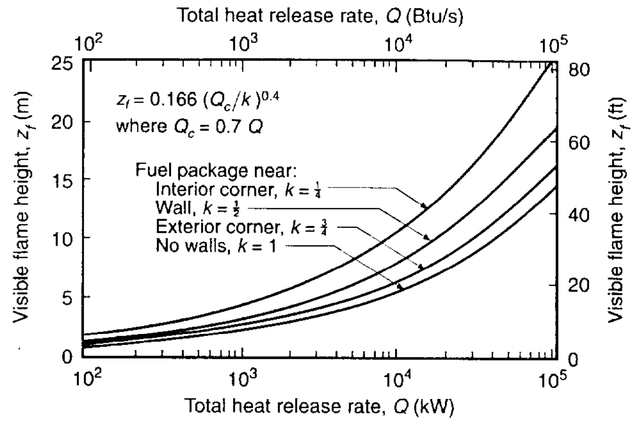

FIG. 7-6C. Flame height vs. fire heat release rate.

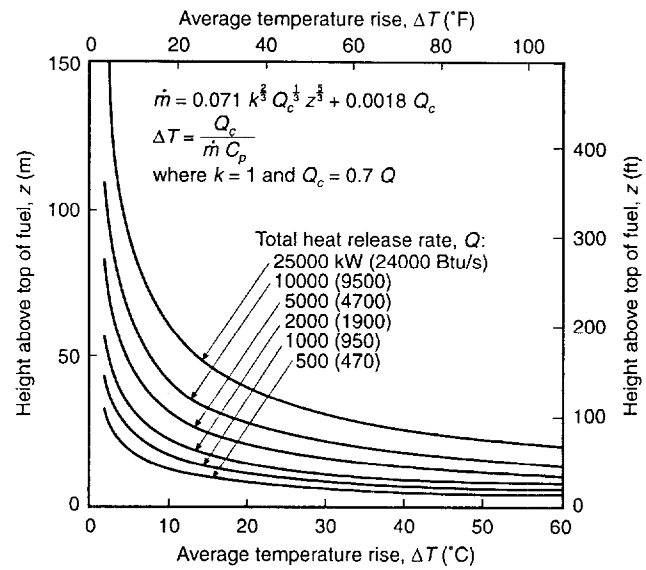

FIG. 7-6D. Average plume temperature rise.

SMOKE MOVEMENT IN THE COLD SMOKE ZONES

As smoke is transmitted from the area of fire origin, it is cooled by entrainment of air; by the transfer of heat from the smoke body to building materials, primarily those in the walls and ceilings; and, as the smoke cools, by radiant energy losses. When smoke from a fire flows through a relatively small crack, the entrainment of cool air on the unexposed side tends to cool the smoke very quickly. When the leakage is through larger openings, there may be less entrainment relative to the mass of smoke movement at such junctures and, therefore, cooling will be slower. Once the smoke has cooled to a significant degree, however, it is transported in the same manner as any other pollutant, and the primary moving forces are those presented by the stack effect, the wind effect, and mechanical air movement systems.

When hot smoke is transported from one area of a building to another through a confined passageway, such as a duct, shaft, or stairwell, there will be little or no cooling due to entrainment. In such cases, cooling will be limited to heat lost by conduction from the moving smoke to the shaft material. Often, this loss is modest, and hot smoke can be transported significant distances with only minor cooling by such confined passageways.

PRINCIPLES OF SMOKE MOVEMENT

Smoke can behave very differently in tall buildings than in low buildings. In the lower buildings, the influences of the fire, such as heat, convective movement, and fire pressures, can be the major factors that cause smoke movement. Smoke removal and venting practices reflect this behavior. In tall buildings, these same factors are complicated by the stack effect, which is the vertical natural air movement through the building caused by the differences in temperatures and densities between the inside and outside air. This stack effect can become an important factor in smoke movement and in building design features used to combat that movement.

The predominant factors that cause smoke movement in tall buildings are the stack effect, the influence of external wind forces, and the forced air movement within the building. The following text describes the theoretical natural air movement, which is affected by the first two factors. Forced air movement caused by the building air-handling equipment is presented in Section 7, Chapter 7, and Section 7, Chapter 13, of this handbook, but it should be noted that air movement can be influenced significantly by the mechanical systems of the building. Many design solutions to the problem of tenability use emergency operation of the mechanical systems.

Flow Through Openings

For a crack, gap, or other opening with a pressure difference across it, a flow will result from the higher pressure to the lower pressure. The *orifice equation* is commonly used to describe such flow:

$$V = CA\sqrt{\frac{2\Delta P}{\rho}}$$

where

V = volumetric flow rate through the path, m³/s;

C = dimensionless flow coefficient;

A = flow area (also called leakage area), m²;

ΔP = pressure difference across path, Pa; and

ρ = density gas in path, kg/m³.

In the context of flows through gaps around doors and through construction cracks, the coefficient is generally in the range of 0.6 to 0.7. For standard air density of $\rho = 1.20$ kg/m³ (0.075 lb/cu ft) and for $C = 0.65$, the flow equation above can be expressed as

$$V = 0.839A\sqrt{\Delta P}$$

where

V = volumetric flow rate through the path, m³/s;

A = flow area (also called leakage area), m²; and

ΔP = pressure difference across path, Pa.

In custom units, this equation is

$$V = 2610A\sqrt{\Delta P}$$

where

V = volumetric flow rate through the path, cu ft/min;

A = flow area (also called leakage area), sq ft; and

ΔP = pressure difference across path, in. of water.

Stack Effect

Under normal conditions, the stack effect can account for a major part of the natural air movement in buildings. During a fire, the stack effect is often responsible for the wide distribution of smoke and toxic gases in high-rise buildings.

The stack effect is characterized by a strong draft from the ground floor to the roof of a tall building. The magnitude of this stack effect is a function of the building height, the air-tightness of the exterior walls, the air leakage between floors of the building, and the temperature difference between the inside and outside of the building.

To illustrate the principle of stack effect, consider the schematic of a box with a single opening near the bottom and another near the top, as shown in Figure 7-6E. The theoretical natural draft between the two openings is caused by the difference in weight of the column of air within the box and that of a corresponding column of air of equal dimensions outside the box. The magnitude of the theoretical natural draft may be computed using the following formula:

$$\Delta P = 2.96HB_{op}\left(\frac{1}{T_o} - \frac{1}{T_1}\right)$$

where

ΔP = theoretical pressure difference, in. of water;

H = vertical distance between the inlet and the outlet, ft;

B_o = barometric pressure, in. of mercury;

T_o = temperature of outside air; and

ρ = density of air at 0°F and 1 atmosphere pressure, lb/cu ft

Assuming values of $B_o = 29.9$ in., and $\rho = 0.0862$ lb/cu ft, this expression reduces to

$$\Delta P = 7.63H\left(\frac{1}{T_o} - \frac{1}{T_i}\right)$$

Vertical air movement in a building is caused by this natural draft or stack effect. The magnitude of the stack effect depends on the difference between the inside and outside temperatures and on the vertical distance between openings. If the inside and outside

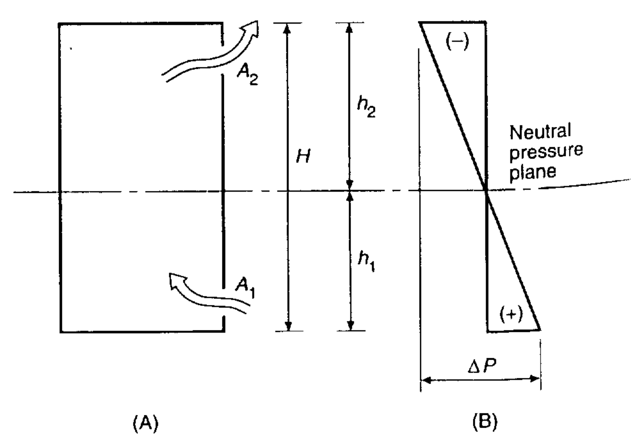

FIG. 7-6E. Air movements caused by pressure (A) and location of neutral pressure plane (B) in a structure without horizontal barriers and with the two openings shown.

temperatures are equal ($T_i = T_o$), no natural air movement takes place. When $T_o \leq T_i$, the air moves vertically upward, with the lower opening acting as the inlet and the upper opening as the outlet. A reverse stack effect occurs when $T_o \geq T_i$. In this case, the upper opening is the inlet and the lower opening becomes the outlet.

Part (B) of Figure 7-6E illustrates the pressures that cause these movements. If it is assumed in this figure that $T_o \leq T_i$, the exterior pressure will be greater than the interior pressure at the lower opening. This is a positive pressure which forces outside air into the building at that location. The outside pressure at the upper opening is lower than the inside pressure, which creates a negative pressure at that location which forces the inside air outside. The pressure distribution between these two locations is assumed to be linear.

If an opening were present in the exterior wall in a region of positive pressure, air would flow into the building. An opening in a region of negative pressure would cause air to flow out of the building. The neutral pressure plane indicates where inside and outside pressures are equal. If there were an opening at this level, air would move neither inward nor outward. The location of the neutral pressure plane in a structure without horizontal barriers and with the two openings shown in Figure 7-6E can be determined from the following relationship:

$$\frac{h_1}{h_2} = \frac{A_2^2 T_o}{A_1^2 T_i}$$

where

h_1 and h_2 represent the distances from the neutral pressure plane to the lower and upper openings, respectively;

A_1 and A_2 represent the cross-sectional areas of the lower and upper openings, respectively; and

T_i and T_o represent the absolute temperatures of the air inside and outside the building, respectively.

The magnitude of the pressures created by the stack effect are described by the equation

$$d_i = 7.63H\left(\frac{1}{T_o} - \frac{1}{T_i}\right).$$

Examination of Figure 7-6F illustrates the significant differences between tall and short buildings with regard to air movement

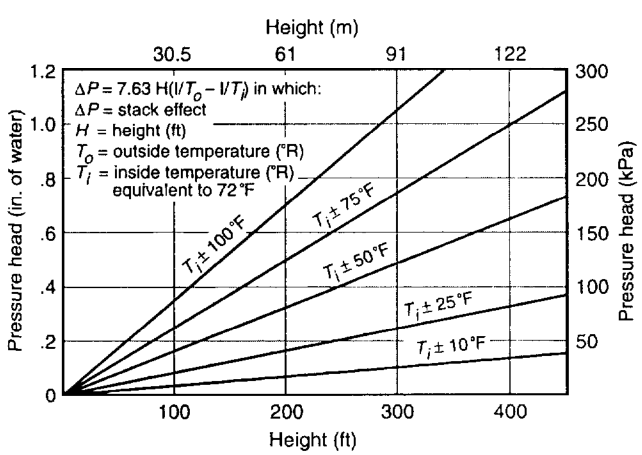

FIG. 7-6F. Stack effect due to height and temperature difference [°C = (°F – 32) × 5/9].

by stack effect. For example, assume that a fire develops a pressure of 0.06 in. of water (25 Pa) in a compartment. Assume further that the outside temperature is 50°F (10°C) lower than the inside temperature and that the fire occurs at the same level as the lower opening. The curve $T_i \pm 50$°F (10°C) indicates that, if the upper outlet were approximately 40 ft (12 m) above the fire, the inlet stack pressure would balance the pressure caused by the fire. A building taller that 40 ft (12 m) would create a greater stack pressure, and, theoretically, the outside air would move into the building.

Influence of Floors and Partitions

The theoretical draft described by Figure 7-6E and the final reduced equation are modified in real buildings by the presence of floors and partitions. These barriers impede the free movement of air, although a significant flow can take place through openings in the assemblies.

The magnitude and location of the leakage areas in a building naturally vary with the building's function and type of construction. The National Research Council of Canada conducted studies of airtightness for major separations on four buildings ranging from 9 to 44 stories high. The measurements were used for computer modeling of the air movement for a simulated 20-story building with a floor plan dimension of 120 by 120 ft (36 by 36 m) and a floor to floor height of 12 ft (3.6 m).[7] The data from the National Research Council of Canada has been established as a table of calculation.[7] The data are given in Table 7-6A.

TABLE 7-6A. ***Typical Leakage Areas for Walls and Floors of Commercial Buildings***

Construction Element	Wall Tightness	Area Ratio A/A_w*
Exterior building walls (includes construction cracks, cracks around windows and doors)	Tight†	0.70×10^{-4}
	Average†	0.21×10^{-3}
	Loose†	0.42×10^{-3}
	Very Loose‡	0.13×10^{-2}
Stairwell walls (includes construction cracks but not cracks around windows or doors)	Tight§	0.14×10^{-4}
	Average§	0.11×10^{-3}
	Loose§	0.35×10^{-3}
Elevator shaft walls (includes construction cracks but not cracks around doors)	Tight§	0.18×10^{-3}
	Average§	0.84×10^{-3}
	Loose§	0.18×10^{-2}
		A/A_F
Floors (includes construction cracks and cracks around penetrations)	Average#	0.52×10^{-4}

*A = leakage area; A_w = wall area; and A_F = floor area.
†Tamura and Shaw 1976.
‡Tamura and Wilson 1966.
§Tamura and Shaw 1976.
#Tamura and Shaw 1978.

These leakage areas are sufficient to allow a substantial air movement throughout the building. Most of the air will flow into vertical shafts, such as stairwells and elevator shafts. Some will flow vertically from floor to floor through the minor openings in the floor-ceiling assembly. This floor-to-floor movement is always caused by a pressure differential between the floors.

Part (A) of Figure 7-6G illustrates the pressure difference characteristics of a building in which stack action causes air movement.

The slopes of the pressure lines represent differences between any two regions at the same height. Airflow from one region to another will always be in the direction of the region whose pressure curve is more to the left. This is illustrated by the airflow directions represented by the arrows in Part (B) of Figure 7-6G.

Wind Effects

Wind action is another important feature in the movement of smoke. Again, tall and short buildings behave somewhat differently in this regard. Figure 7-6H illustrates the air pressure distribution along the four sides and the roof of a building. The plan view of the pressures shows that the windward wall is subjected to an inward pressure, while the leeward wall and the two side walls have an outward pressure, or suction. The flat roof has an upward pressure, with the maximum amount occurring at the windward edge.

These pressures are caused by the movement of a mass of air around and over the structure. A short, wide building will cause the major volume of air to move over the roof, with correspondingly less air movement around the sides. A tall, narrow building, on the other hand, will cause the major volume of air to follow the path of least resistance around the building, with less movement over the top. The velocities of these movements are the primary cause of the amount and directions of the pressures on the building.

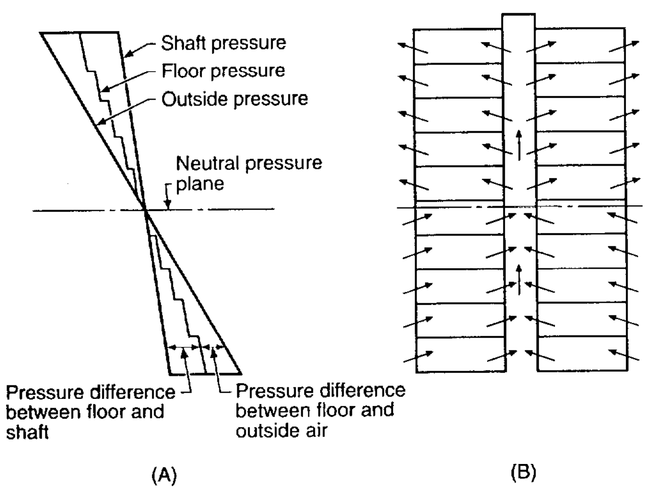

FIG. 7-6G. ***The pressure difference characteristics of a building in which stack action causes air movement.***

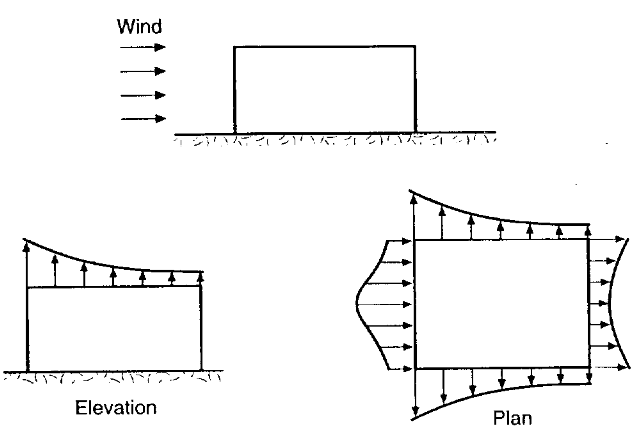

FIG. 7-6H. ***The air pressure distribution along the four sides and the roof of a building.***

Wind velocities and direction vary over any face of a building. The most important effects are:

1. *Wind velocity.* The higher the wind velocity, the greater the effects of the following two influences.
2. *Ground effect.* Unless influenced by unusual arrangements of structures or terrain, the friction and turbulence that occur as air moves over the ground results in the lowest velocity at ground level and increases with increases in height.
3. *Structures.* Buildings and other man-made or natural features, such as trees, can produce localized effects that can increase, decrease, or alter the direction of wind forces.

The effect of wind pressures and suctions modifies the natural air movement within a building. For example, the negative pressure on the roof of a tall building can have an aspirating effect on a vertical shaft opened at the roof level. This can cause the observed draft to exceed the theoretical draft shown in Figure 7-6I.

Horizontal pressures and suctions cause the neutral planes in exterior walls to move. Positive wind pressure would tend to raise the neutral pressure plane, while negative pressure will lower it. Figure 7-6I illustrates the influence of wind action on air movement in a building.

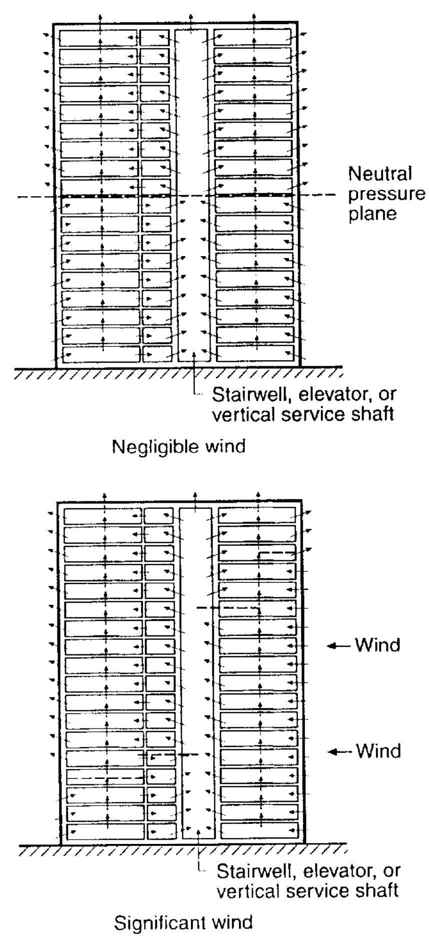

FIG. 7-6I. ***Influence of wind action on air movement in a building. Note how the neutral pressure plane changes location throughout the building in the presence of significant wind.***

SMOKE MANAGEMENT

The term "smoke management," as used in this section, includes all methods that can be used alone or in combination to modify smoke movement for the benefit of occupants or fire fighters or to reduce property damage. The mechanisms of compartmentation, dilution, airflow, pressurization, and buoyancy are used by themselves or in combination to manage smoke conditions in fires. These mechanisms are discussed below.

Compartmentation

Barriers with sufficient fire endurance to remain effective throughout a fire exposure have a long history of providing protection against fire spread. In such fire compartmentation, the walls, partitions, floors, doors, and other barriers provide some level of smoke protection to spaces remote from the fire. This section discusses the use of passive compartmentation, while the use of compartmentation in conjunction with pressurization is discussed later. Many codes, such as NFPA *101®*, *Life Safety Code®*, provide specific criteria for the construction of smoke barriers, including doors and smoke dampers in these barriers. The extent to which smoke leaks through such barriers depends on the size and shape of the leakage paths in the barriers and on the pressure differences across the paths.

There is no formalized analytical method for determining the rate of smoke leakage through barriers and the resulting levels of hazard in areas to be protected. However, emerging fire and smoke transport models can address the smoke leakage through barriers. A first-order approximation of the leakage can be made using the equation for flow through an opening, typical leakage areas listed in Table 7-6A, estimates of the dimensions of paths such as gaps around doors, and the procedures for estimating effective flow areas. More accurate calculations await better data and improved calculation procedures. Full appraisal of the impact of such leakage requires knowledge of the smoke toxicity or an assumed design value of acceptable smoke concentration in protected spaces. A formalized approach to smoke compartmentation should include development of appropriate methods of acceptance testing and routine testing. More effort is needed to increase understanding of the passive capabilities of barriers in order to maximize the usefulness of this oldest and most fundamental method of smoke management.

Dilution

Dilution of smoke is sometimes referred to as smoke purging, smoke removal, smoke exhaust, or smoke extraction. Dilution can be used to maintain an acceptable smoke concentration in a compartment subject to smoke infiltration from an adjacent space. This can be effective if the rate of smoke leakage is small compared to either the total volume of the safeguarded space or the rate of purging air supplied to and removed from the space. Dilution also can be beneficial to the fire service for removing smoke after a fire has been extinguished. Sometimes, when doors are opened, smoke will flow into areas intended to be protected. Ideally, doors will only be open for short periods during evacuation. Smoke that has entered spaces remote from the fire can be purged by supplying outside air to dilute the smoke.

Some people have unrealistic expectations about what dilution can accomplish in the fire space. There is no theoretical or experimental evidence that using a building's heating, ventilation, and air conditioning (HVAC) system for smoke dilution will result in any significant improvement in tenable conditions within the fire space. HVAC systems promote a considerable degree of air mixing within the spaces they serve. Because of this and the fact that building fires can produce very large quantities of smoke, dilution of smoke by an HVAC system in the fire space will not result in any practical improvement in the tenable conditions of that space. Thus, smoke-purging systems intended to improve hazard conditions within a fire space or in spaces connected to a fire space by large openings should not be used.

The following is a simple analysis of smoke dilution for spaces in which there is no fire. At time zero ($t = 0$), a compartment is contaminated with some concentration of smoke, and no further smoke flows into or is generated within the compartment. In addition, the contaminant is considered uniformly distributed throughout the space. The concentration of contaminant in the space can be expressed as:

$$a = \frac{1}{t}\log_e\left(\frac{C_o}{C}\right)$$

$$t = \frac{1}{a}\log_e\left(\frac{C_o}{C}\right)$$

where

C_o = initial concentration of contaminant;

C = concentration of contaminant at time t;

a = dilution rate in number of air changes per min;

t = time after smoke stops entering space or time after which smoke production has stopped, in min; and

e = constant, approximately 2.178.

The concentrations C_o and C must be expressed in the same units, and they can be any units appropriate for the particular contaminant being considered. McGuire, Tamura, and Wilson[8] evaluated the maximum levels of smoke obscuration from a number of fire tests and a number of proposed criteria for tolerable levels of smoke obscuration. Based on this evaluation, they stated that the maximum levels of smoke obscuration are greater by a factor of 100 than those relating to the limit of tolerance. Thus, they indicate that an area can be considered "reasonably safe" with respect to smoke obscuration if its atmosphere will not be contaminated to an extent greater than 1 percent by the atmosphere prevailing in the immediate fire area. It is obvious that such dilution would also reduce the concentrations of toxic smoke components. Toxicity is a more complicated problem, and no parallel statement has been made regarding dilution needed to obtain a safe atmosphere with respect to toxic gases.

In reality, it is impossible to ensure that the concentration of the contaminant is uniform throughout the compartment. Because of the buoyancy, it is likely that higher concentrations would tend to be near the ceiling. Therefore, an exhaust inlet located near the ceiling and a supply outlet located near the floor would probably dilute smoke even faster than indicated by the above equations. Caution should be exercised in locating the supply and exhaust points to prevent the supply air from blowing into the exhaust inlet and thus short circuiting the dilution operation.

EXAMPLE: Smoke purging after the fire is extinguished.

1. After the fire department puts out a fire, the smoke must be cleared quickly so that an inspection can be made to determine if the fire is completely out. If the smoke HVAC system is capable of a dilution rate of six air changes per hr, how long will it take to reduce the smoke concentration to 1 percent of the initial value?

The dilution rate, a, is 0.1 changes per min, and C_o/C is 100.

$$t = \frac{1}{0.1}\log_e(100) = 46 \text{ min to purge smoke to 1 percent of initial value}$$

Considering the fire department's desire to inspect the area quickly, such a long purging time will probably be excessive.

2. If the fire department wants the space to be purged in 10 min, what dilution rate is needed?

   The dilution time, t, is 10 min, and C_o/C is 100.

$$a = \frac{1}{10}\log_e(100) = 0.46 \text{ changes per min (28 changes per hr)}$$

Pressurization

Systems using pressurization produced by mechanical fans are referred to as smoke-control systems in NFPA 92A. Pressurization results in airflows of high velocity in the small gaps around closed doors and in construction cracks, thereby preventing smoke backflows through these openings. The pressurization systems most commonly used are pressurized stairwells and zoned smoke control. Elevator smoke control is less common. Klote and Milke[1] present the public domain computer program ASCOS for analysis of smoke-control systems that use pressurization. Another public domain program, called CONTAM,[9], has extended capabilities for smoke-control analysis and runs more efficiently.

Many pressurized stairwells are designed and built with the goal of providing a tenable environment within the escape route in the event of a building fire. It is obvious that a pressurized stairwell can meet its objectives, even if a small amount of smoke infiltrates the stairwell. The three major design concerns with pressurized stairwells are:

1. Nonuniform pressure differences that occur over the stairwell height.
2. Large pressure fluctuations caused by doors being opened and closed.
3. The location of supply air inlets and fans.

At first, it might appear that the pressure differences from the stairwell to the building would be essentially the same over the height of the stairwell. Unfortunately, this is not the case. For a building without vertical leakage through floors or shafts other than the stairwell, the pressure profile is linear. Of course, this leakage characteristic is not representative of many buildings. However, this case is useful because it has been analytically solved, and it represents a worst case. The analysis has been addressed. It is a worst-case scenario in that its minimum pressure difference is less than that for other, more realistic leakage configurations and its maximum pressure difference is greater than that for other leakage configurations. Computer analysis can be performed to include the effects of more complicated building leakage arrangements.

When a door is opened in a pressurized stairwell, the pressure difference across the remaining closed doors can drop dramatically. The two classes of design concepts that have been used to deal with this problem are over-pressure relief and feedback control. An over-pressure relief system that has gained attention as being simple and cost-effective is the "Canadian System." The essential features of this system are that air is supplied by one or more fans at relatively constant flow rates, and the ground-floor exterior stairwell door opens automatically when the system activates. This system eliminates the source of the most severe pressure fluctuations—the opening and closing of the exterior door.

There is concern about locating supply air inlets near the exterior ground-floor doors of the stairwell. If a supply inlet is located near this door, it is possible that much of the supply air will flow directly through the exterior doorway when it is opened, thus effectively reducing stairwell pressurization. It is believed that locating inlets only one floor away from exterior doors eliminates this potential.

In the late 1960s, the concept of the "pressure sandwich" evolved. This consisted of exhausting the fire floor and pressurizing surrounding floors to limit smoke movement to the fire floor. The pressure sandwich concept has evolved into today's zoned smoke-control systems. According to the concept of zoned smoke control, a building can be divided into a number of smoke zones, each separated from the others by partitions and floors. A smoke-control zone can consist of one floor or more than one floor, or a floor can consist of more than one smoke zone. In the event of fire, pressure differences and airflows produced by mechanical fans can be used to restrict smoke spread to the zone in which the fire began, or the smoke zone. The concentration of smoke in this zone may render it untenable. Accordingly, in zoned smoke-control systems, building occupants should evacuate the zone in which the fire occurs as soon as possible after the fire has been detected.

Airflow

Airflow has been used extensively to manage smoke from fires in subway, railroad, and highway tunnels. Large flow rates of air are needed to control smoke flow, and these flow rates can supply additional oxygen to the fire. Because of the need for complex controls, airflow is not used as extensively in buildings. The control problem consists of having very small flows when a door is closed, and then having those flows increase significantly when that door opens.

Thomas[10] determined that airflow in a corridor in which there is a fire can almost totally prevent smoke from flowing upstream of the fire. As illustrated in Figure 7-6H, the smoke forms a surface that slopes into the direction of the oncoming airflow. Molecular diffusion is believed to result in the transfer of trace amounts of smoke, producing no hazard upstream, just the odor of smoke. There is a minimum velocity below which smoke will flow upstream, and Thomas[10] developed the following empirical relation for this critical velocity. This relation, evaluated at air density of 0.081 lb/cu ft and temperature of 81°F (27°C) is:

$$V_k = 5.68\left(\frac{E}{W}\right)^{1/3}$$

where

V_k = critical air velocity to prevent smoke backflow, ft/min;

E = energy release rate into corridor, Btu/hr; and

W = corridor width, ft.

This relation can be used when the fire is located in the corridor or when the smoke enters the corridor through an open doorway, an air transfer grille, or some other opening. The critical velocities calculated are approximate, because only an approximate value of k was used. However, the critical velocities from this relation are indicative of the kind of air velocities required to prevent smoke backflow from fires of different sizes.

EXAMPLE: Rough estimates of airflow for a doorway.

1. Thomas[10] indicated that his relationship for critical velocity can be used to obtain a rough estimate for doorways. A room fully involved in fire could have an energy release rate on the order of 8×10^6 Btu/hr. What estimate of critical velocity is obtained from the Thomas[10] equation for a door 3 ft (0.9 m) wide?

$$V_k = 5.68\left(8 \times 10^6/3\right)^{1/3} = 800 \text{ ft/min}$$

If the door has an area of 20 sq ft, this would amount to a flow of 1600 cu ft/min.

2. Consideration of a smaller fire, such as a wastebasket fire, may be appropriate for many situations. What flow rate does the Thomas[10] relation indicate is needed to prevent backflow for the above door? A wastebasket fire has an energy release rate near 0.5×10^6 Btu/hr.

$$V_k = 5.68\left(0.5 \times 10^6/3\right)^{1/3} = 300 \text{ ft/min}$$

For a door area of 20 sq ft, this would amount to a flow of 6000 cu ft/min.

Buoyancy in Large Spaces

Buoyancy of hot combustion gases is employed in both fan-powered and nonpowered smoke management systems for large-volume spaces. The spaces where such systems are employed include atria, arcades, covered shopping malls, sports arenas and exhibition halls. In general, these buoyancy systems are used for spaces with floor to ceiling heights of at least 33 ft (10 m). The following are approaches that can be used to manage smoke in large spaces.

1. *Smoke filling:* This approach consists of allowing smoke to fill the large-volume space while occupants evacuate the atrium. This approach applies only to spaces where the smoke filling time is sufficient for both decision making and evacuation. Evacuation time can be estimated by people movement analysis.[11,12] Smoke filling time can be estimated by either computer fire models or by the filling time equations in NFPA 92B.
2. *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. This approach requires an analysis of people movement and a fire model analysis of smoke filling.
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. (See Figure 7-6J.) Design analysis of this system is based on the fact that the mass flow of smoke entering the upper smoke layer equals that of the exhaust. For a fuel package away from walls, the exhaust airflow rates are shown in Figure 7-6K.

Computer fire models include the Harvard Code,[13] ASET,[14] ASET-B,[15] the BRI Model,[16] FIREFORM,[17] CCFM,[18] and CFAST.[19] The University of Maryland has made modifications to CCFM, specifically for atrium smoke management design.[20] Descriptions of zone models are provided by Bukowski,[21] Friedman,[22] Jones,[23] Mitler and Rockett,[24] Mitler,[25] and Quintiere.[26] Klote[27] provides an overview of atrium smoke management and a public domain computer program, entitled "Atrium Smoke Management Engineering Tools" (ASMET).

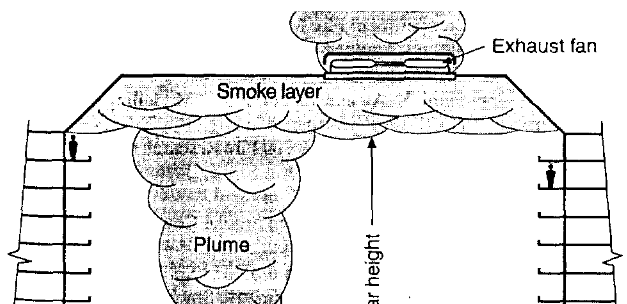

FIG. 7-6J. Atrium smoke exhaust to maintain a smoke-free clear height.

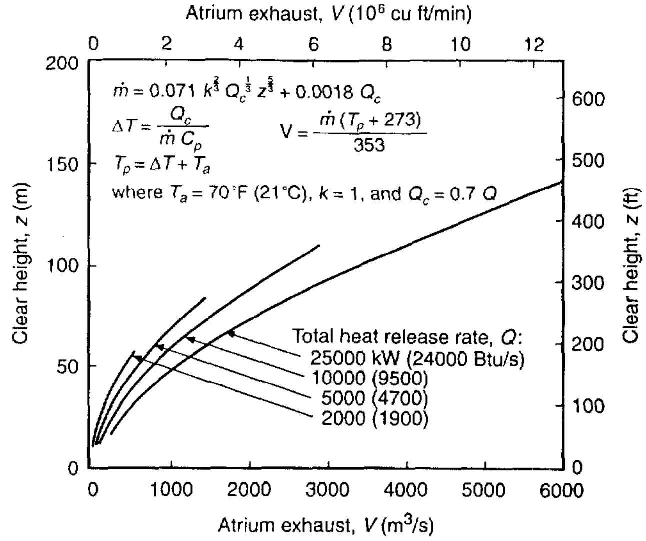

FIG. 7-6K. Atrium exhaust needed to maintain a clear height for various heat release rates.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on smoke movement in buildings discussed in this chapter. (See the latest version of *The NFPA Catalog* for availability of current editions of the following documents.)

NFPA 92A, *Recommended Practice for Smoke Control Systems*

NFPA 92B, *Guide for Smoke Management Systems in Malls, Atria, and Large Areas*

NFPA *101®*, *Life Safety Code®*

NFPA 204M, *Guide for Smoke and Heat Venting*

NFPA 258, *Standard Research Test Method for Determining Smoke Generation of Solid Materials*

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