

CHAPTER 53

FIRE AND SMOKE CONTROL

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SMOKE, which causes the most deaths in fires, consists of air-borne solid and liquid particles and gases produced when a material undergoes pyrolysis or combustion, together with air that is entrained or otherwise mixed into the mass. In building fires, smoke often flows to locations remote from the fire, threatening life and damaging property. Stairwells and elevators frequently fill with smoke, thereby blocking or inhibiting evacuation.

The idea of using pressurization to prevent smoke infiltration of stairwells began to attract attention in the late 1960s. This concept was followed by the idea of the pressure sandwich (i.e., venting or exhausting the fire floor and pressurizing the surrounding floors). Frequently, a building’s HVAC system is used for this purpose. This chapter discusses smoke control systems and fire management in buildings, including the relationship with HVAC. A **smoke control system** is an engineered system that modifies smoke movement for the protection of building occupants, firefighters and property. The focus of code-mandated smoke control is life safety.

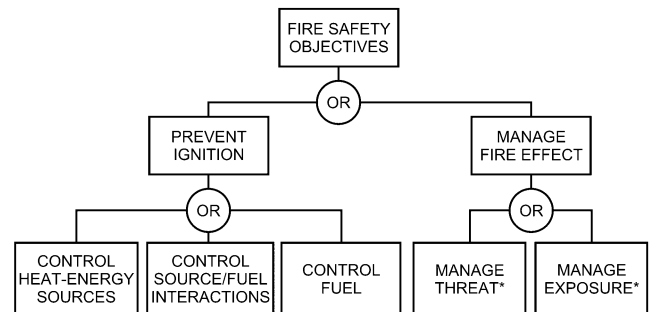
For an extensive technical treatment of smoke control and related topics, see the *Handbook of Smoke Control Engineering* (Klote et al. 2012), referred to in this chapter as the *Smoke Control Handbook*. For those interested in the theoretical foundations of smoke control, the *Smoke Control Handbook* includes an appendix of derivations of equations.

National Fire Protection Association (NFPA) *Standard 92* provides information about smoke control systems for buildings. For further information about heat and smoke venting for large industrial and storage buildings, refer to NFPA *Standard 204*.

The objective of fire safety is to provide some degree of protection for a building’s occupants, the building and property inside it, and neighboring buildings. Various forms of analysis have been used to quantify protection. Specific life safety objectives differ with occupancy; for example, nursing home requirements are different from those for office buildings.

Two basic approaches to fire protection are (1) to prevent fire ignition and (2) to manage fire effects. **Figure 1** shows a decision tree for fire protection. Building occupants and managers have the primary role in preventing fire ignition, though the building design team may incorporate features into the building to support this effort. Because it is impossible to prevent fire ignition completely, managing fire’s effects is significant in fire protection design. Examples include compartmentation, suppression, control of construction materials, exit systems, and smoke control. The *SFPE Handbook of Fire Protection Engineering* (SFPE 2008) and the *Fire Protection Handbook* (NFPA 2008) contain detailed fire safety information.

Historically, fire safety professionals have considered the HVAC system a potentially dangerous penetration of natural building



*Note: Smoke control is one of many fire protection tools that can be used to help manage the threat and exposure of fire.

Fig. 1 Simplified Fire Protection Decision Tree

membranes (walls, floors, etc.) that can readily transport smoke and fire. For this reason, HVAC has traditionally been shut down when fire is discovered; this prevents fans from forcing smoke flow, but does not prevent ducted smoke movement caused by buoyancy, stack effect, or wind. Smoke control methods have been developed to address smoke movement; however, smoke control should be viewed as only one part of the overall building fire protection system.

1. FIRE MANAGEMENT

Although most of this chapter discusses smoke control, fire management at HVAC penetrations is also a concern. The most efficient way to limit fire damage is through compartmentation. Fire-rated assemblies (e.g., floor or walls) keep the fire in a given area for a specific period. However, fire can easily pass through openings for plumbing, HVAC ductwork, communication cables, or other services. Therefore, fire stop systems are installed to maintain the rating of the fire-rated assembly. The rating of a fire stop system depends on the number, size, and type of penetrations, and the construction assembly in which it is installed.

Performance of the entire fire stop system, which includes the construction assembly with its penetrations, is tested under fire conditions by recognized independent testing laboratories. ASTM *Standard E814* and UL *Standard 1479* describe ways to determine performance of **through-penetration fire stopping (TPFS)**.

TPFS is required by building codes under certain circumstances for specific construction types and occupancies. In the United States, the model building codes require that most penetrations pass ASTM *Standard E814* testing. TPFS classifications are published by testing laboratories. Each classification is proprietary, and each applies to use with a specific set of conditions, so numerous types are usually required on any given project.

The preparation of this chapter is assigned to TC 5.6, Control of Fire and Smoke.

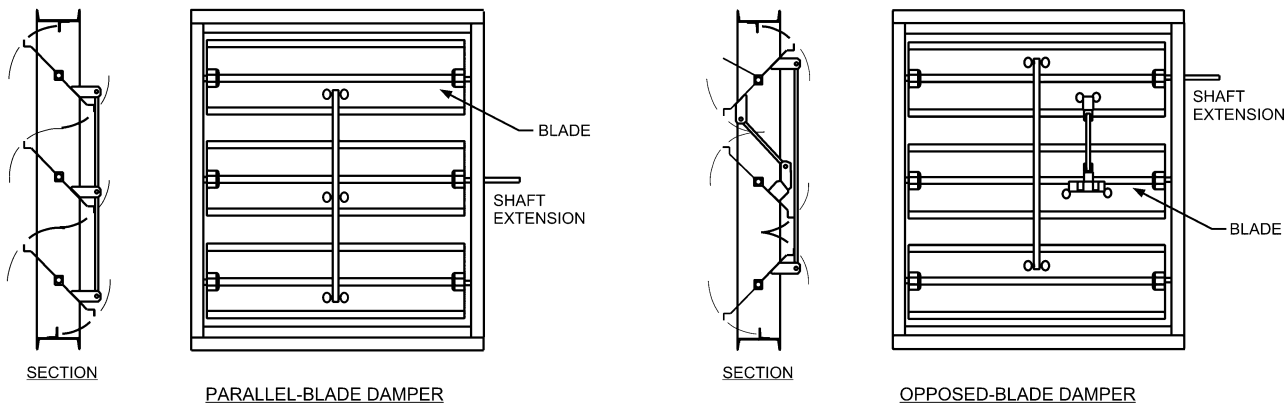


Fig. 2 Multiblade Dampers

The construction manager and general contractor, not the architects and engineers, make work assignments. Sometimes they assign fire stopping to the discipline making the penetration; other times, they assign it to a specialty fire-stopping subcontractor. The Construction Specifications Institute (CSI) assigns fire-stopping specifications to Division 7, which

- Encourages continuity of fire-stopping products on the project by consolidating their requirements (e.g., TPFS, expansion joint fire stopping, floor-to-wall fire stopping, etc.)
- Maintains flexibility of work assignments for the general contractor and construction engineer
- Encourages prebid discussions between the contractor and subcontractors regarding appropriate work assignments

2. FIRE AND SMOKE DAMPERS

Dampers are used for one or more of the following purposes: (1) balancing flow by adjusting airflow in HVAC system ducts, (2) controlling flow (for HVAC purposes), (3) resisting passage of fire (**fire dampers**), and (4) resisting passage of smoke (**smoke dampers**). Dampers that are intended to resist the passage of both fire and smoke are called **combination fire and smoke dampers**. For more detailed information about dampers, including pressure losses, flow characteristics, actuators, installation, and balancing, see Felker and Felker (2009).

Fire Dampers

Fire dampers are intended to prevent the spread of flames from one part of the building to another through the ductwork. They are not expected to prevent airflow between building spaces, because gaps of up to 9.5 mm are allowed for operating clearances. Fire dampers are rated to indicate the time they can be exposed to flames and still maintain their integrity, with typical ratings of 3 h, 1 1/2 h, 1 h, and less than 1 h. Fire dampers are two-position devices (open or closed), and are usually of either the multiblade (Figure 2) or curtain design (Figure 3). Most multiblade fire dampers are held open by a fusible link and are spring loaded. In a fire, hot gases cause this link to come apart so that the spring makes the blades slam shut. Some manufacturers use other heat-responsive devices in place of fusible links. Typically, curtain dampers are also held open by a fusible link that comes apart when heated. Curtain dampers often rely on gravity to make the blades close off the opening, but horizontal (ceiling) curtain dampers must have spring closure.

In the United States, fire dampers are usually made and labeled in accordance with UL *Standard* 555. This standard addresses fire dampers intended for use (1) where air ducts penetrate or terminate at openings in walls or partitions, (2) in air transfer openings, and (3) where air ducts extend through floors.

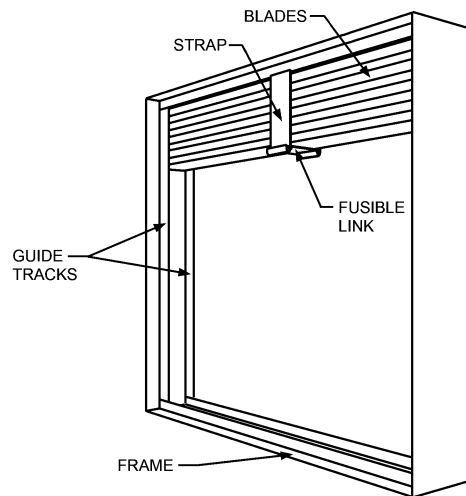


Fig. 3 Curtain Fire Damper

Fire dampers are evaluated for use as static, dynamic, or combination fire and smoke dampers. Static dampers are for applications where the damper will never have to close against an airstream, such as when HVAC systems are automatically shut down when a fire is detected. Dynamic dampers are for applications where the damper may be required to close against airflow, such as an HVAC system that remains operational for smoke control purposes. UL *Standard* 555 also applies to ceiling dampers and ceiling diffusers intended for use in hourly-rated fire-resistive floor/ceiling and roof/ceiling assemblies.

Smoke Dampers

Smoke dampers are intended to seal tightly to prevent the spread of smoke from one part of the building to another through the building's ductwork, and to allow an engineered smoke control system to build up pressures across zone boundaries. A smoke damper is not required to withstand high temperature and will not prevent a fire from spreading. Smoke dampers are of the multiblade design (Figure 2), and may be either two-position devices (open and closed), or may be modulated between the open and closed positions to serve as both a smoke damper and a control damper.

In the United States, smoke dampers are usually made and classified for leakage in accordance with UL *Standard* 555S. This standard includes construction requirements; air leakage tests; and endurance tests of cycling, temperature degradation, salt-spray exposure, and operation under airflow.

Table 1 UL 555S Leakage Classifications for Smoke Dampers

Leakage Class	Maximum Leakage at		
	1.1 kPa, m ³ /(s·m ²)	2.1 kPa, m ³ /(s·m ²)	3.1 kPa, m ³ /(s·m ²)
I	0.041	0.056	0.071
II	0.102	0.142	0.178
III	0.406	0.569	0.711

Each smoke damper needs to pass testing for (1) reliability, (2) temperature resistance, and (3) air leakage resistance. The operational test confirms proper smoke damper operation after 20 000 cycles or 100 000 cycles for modulating smoke dampers. The temperature test confirms proper smoke damper operation after 30 min exposure to elevated temperatures. Smoke dampers must meet the requirements at a minimum temperature of 121°C, and may receive higher temperature ratings in increments of 56°C.

After the reliability and temperature resistance tests, the air leakage test is conducted. UL defines air leakage classes by the maximum allowable leakage through the closed smoke damper at a minimum pressure difference of 1.1 kPa. The smoke damper classes are I, II, and III, and the leakages of these damper classes are listed in [Table 1](#).

Designers can use these leakage classes to specify smoke dampers. At a location where very little smoke leakage is acceptable, a class I damper may be needed. Where some smoke leakage will not adversely impact smoke control performance, a class II or III damper may be appropriate. Combination fire and smoke dampers comply with the dynamic fire damper requirements of UL *Standard 555* and with the smoke damper requirements of UL *Standard 555S*.

3. SMOKE EXHAUST FANS

Typically, smoke control systems for buildings are designed to avoid the need for operation at elevated temperatures. For zoned smoke control systems, usually the zone being exhausted is much larger than the fire space, and this limits the gas temperature at the exhaust fan. For atrium smoke control systems, air is entrained in the smoke plume that rises above the fire, and this entrained air reduces the temperature of the smoke exhaust.

ASHRAE *Standard 149-2000* (reaffirmed in 2009) established uniform methods of laboratory testing and test documentation for fans used to exhaust smoke in smoke control systems.

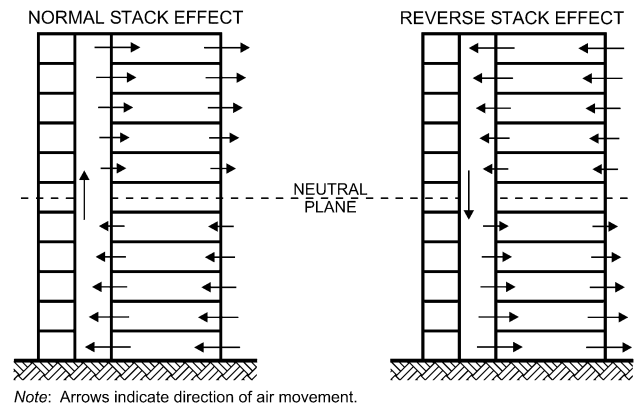
4. DESIGN WEATHER DATA

Chapter 2 of the *Smoke Control Handbook* lists design climatological data for design of smoke control systems for many locations in the United States, Canada, and other countries. These data consists of winter temperature, summer temperature, and wind speed. Standard barometric pressure at these locations is also listed.

Wind is measured at weather stations, which are often at airports. Because local terrain has a significant effect on wind, wind speeds at project sites are usually very different from those measured at neighboring weather stations. For information about adjusting design wind speed to a project site, see Chapter 3 of the *Smoke Control Handbook* and Chapter 24 of the 2013 *ASHRAE Handbook—Fundamentals*.

5. SMOKE MOVEMENT

A smoke control system must be designed so that it is not overpowered by the driving forces that cause smoke movement: stack effect, buoyancy, expansion, wind, forced ventilation, and elevator piston effect. In a building, fire smoke is usually moved by a combination of these forces.

**Fig. 4** Air Movement Caused by Normal and Reverse Stack Effect

Stack Effect

It is common to have an upward flow of air in building shafts during winter. These shafts include stairwells, elevator shafts, dumbwaiters, and mechanical shafts. The upward flow is caused by the buoyancy of warm air relative to the cold outdoor air. This upward flow is similar to the upward flow in smoke stacks, and it is from this analogy that the upward flow in shafts got the name stack effect. In summer, flow in shafts is downward. Upward flow in shafts is called **normal stack effect**, and downward flow is called **reverse stack effect**.

[Figure 4](#) shows both kinds of stack effect. In normal stack effect, air flows into the building below the neutral plane, flows up building shafts, and out of the building above the neutral plane. The neutral plane is a horizontal plane where pressure inside the shaft equals outdoor pressure, and is often near the midheight of a building.

At standard atmospheric pressure, the pressure difference caused by either normal or reverse stack effect is expressed as

$$\Delta p_{SO} = 3460 \left(\frac{1}{T_O} - \frac{1}{T_S} \right) z \quad (1)$$

where

$$\begin{aligned} \Delta p_{SO} &= \text{pressure difference from shaft to outdoors, Pa} \\ T_S &= \text{absolute temperature of shaft, K} \\ T_O &= \text{absolute temperature of outdoors K} \\ z &= \text{distance above neutral plane, m} \end{aligned}$$

[Figure 5](#) diagrams the pressure difference between a building shaft and the outdoors. A positive pressure difference indicates that shaft pressure is higher than the outdoor pressure, and a negative pressure difference indicates the opposite. For a building 60 m tall with a neutral plane at midheight, an outdoor temperature of -18°C (255 K), and an indoor temperature of 21°C (294 K), the maximum pressure difference from stack effect is 54 Pa. This means that, at the top of the building, pressure inside a shaft is 54 Pa greater than the outdoor pressure. At the base of the building, pressure inside a shaft is 54 Pa lower than the outdoor pressure.

Smoke movement from a building fire can be dominated by stack effect. In a building with normal stack effect, the existing air currents (as shown in [Figure 4](#)) can move smoke considerable distances from the fire origin. If the fire is below the neutral plane, smoke moves with building air into and up the shafts. This upward smoke flow is enhanced by buoyancy forces from the smoke temperature. Once above the neutral plane, smoke flows from the shafts into the

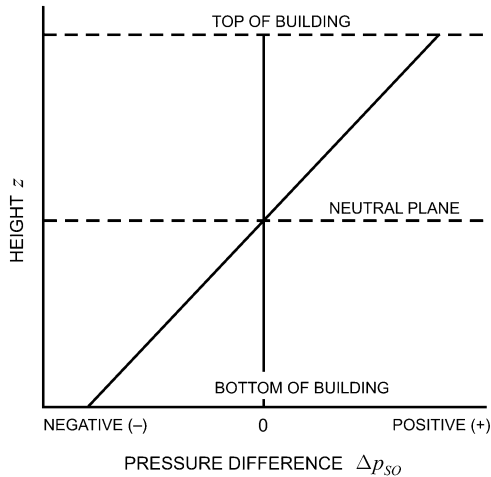


Fig. 5 Pressure Difference Between Building Shaft and Outdoors Caused by Normal Stack Effect

upper floors of the building. If leakage between floors is negligible, floors below the neutral plane (except the fire floor) remain relatively smoke free until more smoke is produced than can be handled by stack effect flows.

Smoke from a fire located above the neutral plane is carried by building airflow to the outdoors through exterior openings in the building. If leakage between floors is negligible, all floors other than the fire floor remain relatively smoke free until more smoke is produced than can be handled by stack effect flows. When leakage between floors is considerable, smoke flows to the floor above the fire floor.

Air currents caused by reverse stack effect (see Figure 4) tend to move relatively cool smoke down. In the case of hot smoke, buoyancy forces can cause smoke to flow upward, even during reverse stack effect conditions.

Caution: It is a myth that the pressure difference caused by stack effect is nearly proportional to the temperature difference between the *building* and the outdoors. Instead, this pressure difference is nearly proportional to the temperature difference between a *shaft* and the outdoors. Looking at Figure 4, it is easy to see how the shaft and building temperatures might be considered identical. Often, they are the same. However, shafts that have one or more walls on the outside of the building tend to be relatively cold in winter and warm in summer, and this can have a major influence on stack effect.

For a building with shafts of various heights and different shaft temperatures, the flows become very complicated and would not resemble those in Figure 4. Each shaft could have its own neutral plane with respect to the outdoors, and may have more than one neutral plane. Equation (1) is not applicable for such complicated buildings, but the flows and pressures in such buildings can be analyzed by a network flow model such as CONTAM (see the section on Computer Analysis).

Buoyancy

High-temperature smoke has buoyancy because of its reduced density. At sea level, the pressure difference between a fire compartment and its surroundings can be expressed as follows:

$$\Delta p_{FS} = 3460z \left(\frac{1}{T_S} - \frac{1}{T_F} \right) \quad (2)$$

where

Δp_{FS} = pressure difference from fire compartment to surroundings, Pa
 T_F = average absolute temperature of fire compartment, K
 T_S = absolute temperature of surroundings, K
 z = distance above neutral plane, m

The neutral plane is the plane of equal hydrostatic pressure between the fire compartment and its surroundings. For a fire with a fire compartment temperature at 800°C (1073 K), the pressure difference 1.5 m above the neutral plane is 13 Pa. Fang (1980) studied pressures caused by room fires during a series of full-scale fire tests and found a maximum pressure difference of 16 Pa across the burn room wall at the ceiling. Much larger pressure differences are possible for tall fire compartments, where the distance z from the neutral plane can be larger.

In sprinkler-controlled fires, the temperature in the fire room remains at that of the surroundings except for a short time before sprinkler activation. Sprinklers are activated by the **ceiling jet**, which is a layer of hot gas under the ceiling. The ceiling jet's maximum temperature depends on the fire's location, activation temperature of the sprinkler, and thermal lag of the sprinkler heat-responsive element. For most residential and commercial applications, the ceiling jet is between 80 and 150°C. In Equation (2), T_F is the average temperature of the fire compartment.

For a sprinkler-controlled fire,

$$T_F = \frac{T_S(H - H_J) + T_J H_J}{H} \quad (3)$$

where

H = floor-to-ceiling height, m
 H_J = thickness of ceiling jet, m
 T_F = average absolute temperature of fire compartment, K
 T_S = absolute temperature of surroundings, K
 T_J = absolute temperature of ceiling jet, K

For example, for $H = 2.5$ m, $H_J = 0.1$ m, $T_S = 20 + 273 = 293$ K, and $T_J = 150 + 273 = 423$ K,

$$T_F = [293(2.5 - 0.1) + 423 \times 0.1] / 2.5 = 298 \text{ K or } 25^\circ\text{C}$$

In Equation (2), this value of T_F and z of 1.5 m results in a pressure difference of 0.5 Pa, which is insignificant for smoke control applications.

Expansion

Energy released by a fire can also move smoke by expansion. In a fire compartment with only one opening to the building, building air flows in, and hot smoke flows out. Neglecting the added mass of the fuel, which is small compared to airflow, the ratio of volumetric flows can be expressed as a ratio of absolute temperatures:

$$\frac{V_{out}}{V_{in}} = \frac{T_{out}}{T_{in}} \quad (4)$$

where

V_{out} = volumetric flow rate of smoke out of fire compartment, m³/s
 V_{in} = volumetric flow rate of air into fire compartment, m³/s
 T_{out} = absolute temperature of smoke leaving fire compartment, K
 T_{in} = absolute temperature of air entering fire compartment, K

For smoke at 700°C (973 K) and entering air at 20°C (293 K), the ratio of volumetric flows is 3.32. Note that absolute temperatures are used in the calculation. In such a case, if air enters the compartment at 1.5 m³/s, then smoke flows out at 5.0 m³/s, with the gas expanding to more than three times its original volume.

For a fire compartment with open doors or windows, the pressure difference across these openings caused by expansion is negligible. However, for a tightly sealed fire compartment, the pressure differences from expansion may be important.

Wind

In many instances, wind can have a pronounced effect on smoke movement within a building. The pressure that wind exerts on a wall is

$$p_w = \frac{1}{2} C_w \rho_o U_H^2 \quad (5)$$

where

$$\begin{aligned} p_w &= \text{wind pressure, Pa} \\ C_w &= \text{pressure coefficient} \\ \rho_o &= \text{outdoor air density, kg/m}^3 \\ U_H &= \text{velocity at wall height } H, \text{ m/s} \end{aligned}$$

The pressure coefficient C_w depends on wind direction, building geometry, and local obstructions to the wind. The pressure coefficients are in the range of -0.8 to 0.8 , with positive values for windward walls and negative for leeward walls.

Frequently, a window breaks in the fire compartment. If the window is on the leeward side of the building, the negative pressure caused by the wind vents the smoke from the fire compartment. This reduces smoke movement throughout the building. However, if the broken window is on the windward side, wind forces the smoke throughout the fire floor and to other floors, which endangers the lives of building occupants and hampers firefighting. Wind-induced pressure in this situation can be large and can dominate air movement throughout the building.

Forced Ventilation

Modern HVAC systems are built of materials intended to withstand fires, and either shut down in the event of a fire or go into a smoke control mode of operation. For details on the latter approach, see the section on Zoned Smoke Control.

Elevator Piston Effect

The transient pressures and flows produced when an elevator car moves in a shaft are called **piston effect**, and can pull smoke into a normally pressurized elevator lobby or elevator shaft. For a validated analysis of piston effect, see Klote (1988) and Klote and Tamura (1986, 1987).

When an elevator car rises, the pressure difference across an elevator door increases until the car reaches that floor. When the car passes the floor, the pressure difference suddenly drops and then increases. For elevators with lobbies that have closed doors (enclosed lobbies), the pressure difference across the closed lobby doors reacts in a similar way to elevator car motion.

For a car traveling from the bottom to the top of the shaft, the largest value of pressure difference from stack effect is at the top of the shaft; for a car traveling from the top to the bottom, the largest value is at the bottom of the shaft. This largest value of pressure difference is called the **upper limit of piston effect**.

The upper limit of piston effect for an elevator with enclosed lobbies is

$$\Delta P_{u,ir} = \frac{\rho}{2} \left(\frac{A_s A_e U}{A_a A_{ir} C_c} \right)^2 \quad (6)$$

where

$$\begin{aligned} \Delta p_{u,si} &= \text{upper limit pressure difference from shaft to building, Pa} \\ \rho &= \text{air density in hoistway, kg/m}^3 \\ A_s &= \text{cross-sectional area of shaft, m}^2 \\ A_{ir} &= \text{leakage area between building and lobby, m}^2 \\ A_a &= \text{free area around elevator car, m}^2 \\ A_e &= \text{effective area, m}^2 \\ U &= \text{elevator car velocity, m/s} \\ C_c &= \text{flow coefficient for flow around car} \end{aligned}$$

The flow coefficient C_c was determined experimentally at about 0.94 for a multiple-car hoistway and 0.83 for a single-car hoistway.

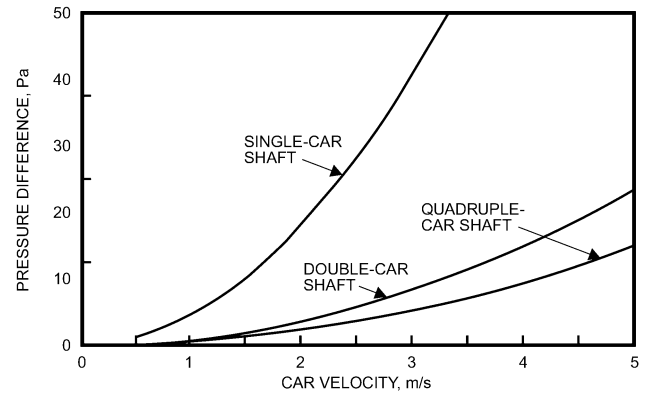


Fig. 6 Calculated Upper Limit of Piston Effect Across Elevator Lobby Doors.

The free area around the elevator car is the cross-sectional area of the shaft less the cross-sectional area of the car. Effective areas are discussed in the section on Height Limit.

Figure 6 shows the upper limit of piston effect from the lobby to the building for normal elevator car velocities from 1 to 5 m/s. All elevator velocities are in this range except for those in extremely tall buildings.

6. SMOKE CONTROL

In this chapter, smoke control includes all methods that can be used singly or in combination to modify smoke movement to protect occupants or firefighters or reduce property damage. These methods are (1) compartmentation, (2) dilution, (3) pressurization, (4) air-flow, and (5) buoyancy. These mechanisms are discussed in the following sections.

Compartmentation

Barriers that can remain effective throughout a fire exposure have long been used to protect against fire spread. In this approach, walls, partitions, floors, doors, and other barriers provide some level of smoke protection to spaces remote from the fire. Passive smoke control consists of using barriers alone (or without pressurization). Using compartmentation with pressurization is discussed in the section on Pressurization (Smoke Control). Passive smoke control systems can be analyzed with the goal of providing a tenable environment at specific locations during a fire. For more information, see the section on Tenability Systems. Many codes, such as the *Life Safety Code*[®] (NFPA 2012) and the *International Building Code*[®] (ICC 2012), provide specific criteria for construction of passive smoke barriers (including doors) and their smoke dampers. The extent to which smoke leaks through such barriers depends on the size and shape of the leakage paths in the barriers and the pressure difference across the paths.

Dilution Remote from Fire

Smoke dilution is sometimes referred to as **smoke purging**, **smoke removal**, **smoke exhaust**, or **smoke extraction**. Dilution can be used to maintain acceptable gas and particulate concentrations in a compartment subject to smoke infiltration from an adjacent space. It 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. Also, dilution can be beneficial to the fire service for removing smoke after a fire has been extinguished. Sometimes, when doors are opened, smoke flows into areas intended to be protected. Ideally, the doors are only open for short periods during evacuation. Smoke that

has entered spaces remote from the fire can be purged by supplying outdoor air to dilute the smoke.

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 considered contaminated with some concentration of smoke and no more smoke flows into the compartment or is generated in it. Further, the contaminant is considered to be uniformly distributed throughout the space. The concentration of contaminant in the space can be expressed as

$$\frac{C}{C_0} = e^{-at} \quad (7)$$

and the dilution rate can be calculated from

$$a = \frac{1}{t} \ln\left(\frac{C_0}{C}\right) \quad (8)$$

where

- C_0 = initial concentration of contaminant
- C = concentration of contaminant at time t
- a = dilution rate, air changes per minute
- t = time after smoke stops entering space or smoke production has stopped, min
- e = base of natural logarithm (approximately 2.718)

Concentrations C_0 and C must be expressed in the same units, but can be any units appropriate for the particular contaminant being considered.

In reality, it is impossible to ensure that the concentration of the contaminant is uniform throughout the compartment. Because of buoyancy, it is likely that concentrations are higher near the ceiling. Therefore, exhausting smoke near the ceiling and supplying air near the floor probably dilutes smoke even more quickly than indicated by Equation (8). Supply and exhaust points should be placed to prevent supply air from blowing into the exhaust inlet, thereby short-circuiting the dilution.

Example 1. A space is isolated from a fire by smoke barriers and self-closing doors, so that no smoke enters the compartment when the doors are closed. When a door is opened, smoke flows through the open doorway into the space. If the door is closed when the contaminant in the space is 20% of the burn room concentration, what dilution rate is required to reduce the concentration to 1% of that in the burn room in 6 min?

Solution. Time $t = 6$ min and $C_0/C = 20$. From Equation (8), the dilution rate is about 0.5 air changes per minute, or 30 air changes per hour.

Caution About Dilution near Fire: Some people have unrealistic expectations about what dilution can accomplish in the fire space. Neither theoretical nor experimental evidence indicates that using a building's HVAC system for smoke dilution significantly improves tenable conditions in a fire space. The exception is an unusual space where the fuel is such that fire size cannot grow above a specific limit, such as in some tunnels and underground transit situations. Because HVAC systems promote a considerable degree of air mixing in the spaces they serve and because very large quantities of smoke can be produced by building fires, it is generally believed that smoke dilution by an HVAC system in the fire space does not improve tenable conditions in that space. Thus, any attempt to improve hazard conditions in the fire space, or in spaces connected to the fire space by large openings, with smoke purging will be ineffective.

Pressurization

Many smoke control systems use mechanical fans to control smoke by pressurization. Pressure difference across a barrier can control smoke movement by preventing smoke on the low-pressure side of the barrier from migrating to the high-pressure side. Pressurization can control smoke from a fire remote from a barrier, or from a very large fire located next to a barrier (Figure 7).

Frequently, in field tests of smoke control systems, pressure differences across partitions or closed doors fluctuate by 5 Pa. These fluctuations are generally attributed to wind, although they could have been caused by the HVAC system or some other source. To control smoke movement, the pressure difference produced by a smoke control system must be large enough to overcome pressure fluctuations, stack effect, smoke buoyancy, and wind pressure, but not so large that the door is difficult to open.

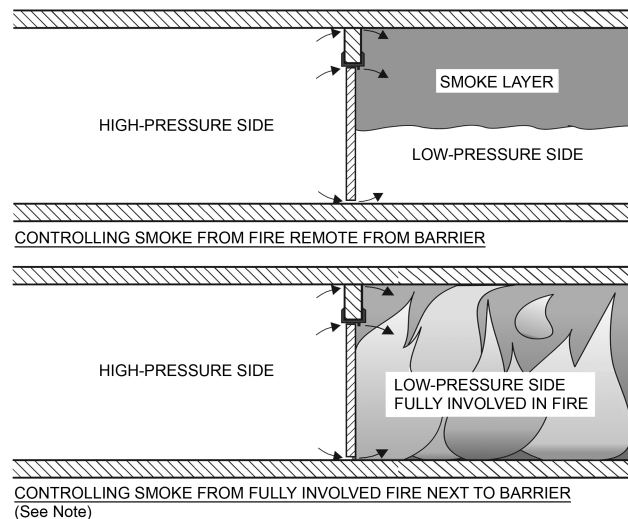
Opposed Airflow

Airflow can be used to control smoke flow in many applications, including buildings, rail tunnels, and highway tunnels, if the air velocity equals or exceeds the limiting velocity (Figure 8). For information about rail and highway tunnels, see Chapter 15. For control of smoke between an atrium and a communicating space, see NFPA *Standard 92* and the limiting velocity equations in Chapter 15 of the *Smoke Control Handbook*.

Airflow is not used much in buildings because of the very large amounts of airflow needed, and (more importantly) because airflow can supply oxygen to the fire, which can result in catastrophic failure. Even full sprinkler protection does not completely eliminate this risk. For any application that uses the airflow approach, this failure mode must be addressed in the design analysis.

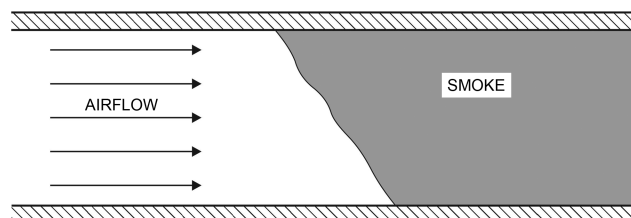
Buoyancy

Buoyancy of hot combustion gases is used for smoke control in large-volume spaces such as atriums. A smoke plume rises above the fire to form a smoke layer under the ceiling of the large volume space. The smoke plume entrains air from the surroundings. The



Note: A fully involved fire is a very large fire such that all the materials in fire space that can burn are burning.

Fig. 7 Smoke Flow Controlled by Pressurization



Note: Airflow can control smoke flow if air velocity is large enough.

Fig. 8 Opposed Airflow Controlling Smoke Flow

mass flow of the plume increases with height, and the plume temperature decreases with height.

7. PRESSURIZATION SYSTEM DESIGN

Door-Opening Forces

The pressure difference across a barrier must not result in door-opening forces that exceed the maximum values stipulated in codes. For example, in the *Life Safety Code*[®] (NFPA *Standard* 101), this maximum force is 133 N.

The force required to open a side-hinged swinging door is the sum of the forces to overcome the pressure difference across the door and to overcome the door closer. This does not include forces from friction, which are insignificant compared to the other forces for properly adjusted and maintained doors. This can be expressed as

$$F = F_{dc} + \frac{WA\Delta p}{2(W-d)} \quad (9)$$

where

- A = door area, m²
- d = distance from doorknob to knob side of door, m
- F = total door-opening force, N
- F_{dc} = door closer force, N
- W = door width, m
- Δp = pressure difference, Pa

This relation assumes that the door-opening force is applied at the knob. Door-opening force caused by pressure difference can be determined from Equation (9). For example, for a side-hinged swinging door 0.914 m wide by 2.13 m high with a door closer that requires 40 N of force, a pressure difference across it of 87 Pa, and a knob that is 76 mm from the edge of the door, the door-opening force is 132 N.

Flow and Pressure Difference

The primary equation used for analysis of pressurization smoke control systems is the orifice equation:

$$m = CA\sqrt{2\rho\Delta p} \quad (10)$$

Alternatively, Equation (10) can be expressed in terms of volumetric flow:

$$V = CA\sqrt{\frac{2\Delta p}{\rho}} \quad (11)$$

where

- m = mass flow through the path, kg/s
- V = volumetric flow, m³/s
- C = flow coefficient
- A = flow area (or leakage area), m²
- Δp = pressure difference across path, Pa
- ρ = gas density in path, kg/m³

Equations (10) and (11) are equivalent forms of the same orifice equation. Airflow paths must be identified and evaluated in smoke control system design. Some leakage paths are obvious, such as cracks around closed doors, open doors, elevator doors, windows, and air transfer grilles. Construction cracks in building walls are less obvious but no less important.

The flow area of most large openings, such as open windows, can be calculated easily. However, flow areas of cracks are more difficult to evaluate. The area of these leakage paths depends on quality of work (e.g., how well a door is fitted or how weatherstripping is installed). For many flow paths in buildings, a flow coefficient of 0.65 is used. The open doors of pressurized stairwells commonly have stationary vortices that reduce flow significantly (Cresci 1973;

Table 2 Typical Flow Areas of Walls and Floors of Commercial Buildings

Construction Element	Wall Tightness	Area Ratio A/A_W^*
Exterior building walls (includes construction cracks and cracks around windows and doors)	Tight	5.0×10^{-5}
	Average	1.7×10^{-4}
	Loose	3.5×10^{-4}
	Very Loose	1.2×10^{-3}
Stairwell walls (includes construction cracks but not cracks around windows or doors)	Tight	1.4×10^{-5}
	Average	1.1×10^{-4}
	Loose	3.5×10^{-4}
Elevator shaft walls (includes construction cracks but not cracks around doors)	Tight	1.8×10^{-4}
	Average	8.4×10^{-4}
	Loose	1.8×10^{-3}
		A/A_F^*
Floors (includes construction cracks and gaps around penetrations)	Tight	6.6×10^{-6}
	Average	5.2×10^{-5}
	Loose	1.7×10^{-4}

* A = leakage area; A_W = wall area; A_F = floor area.

Klote and Bodart 1985). These vortices are thought to be caused by asymmetric flow from the stairs, and stationary vortices can be expected at many open doors in other locations of smoke control systems. For open doors in stairwells, the geometric area of the opening should be used for the flow area, with a flow coefficient of 0.35.

Typical leakage areas for walls and floors of commercial buildings are tabulated as area ratios in Table 2. These data are based from field tests performed by the National Research Council of Canada (Shaw et al. 1993; Tamura and Shaw 1976a, 1976b, 1978; Tamura and Wilson 1966). Considerable leakage data through building components are also provided in Chapter 3 of the *Smoke Control Handbook*.

Design Pressure Differences

Both the maximum and minimum allowable pressure differences across the boundaries of smoke control should be considered. The maximum allowable pressure difference should not cause excessive door-opening forces.

The minimum allowable pressure difference across a boundary of a smoke control system might be the difference such that no smoke leakage occurs during building evacuation. In this case, the smoke control system must produce sufficient pressure differences to overcome forces of wind, stack effect, or buoyancy of hot smoke. Pressure differences caused by wind and stack effect can be large in the event of a broken window in the fire compartment. Evaluation of these pressure differences depends on evacuation time, rate of fire growth, building configuration, and the presence of a fire suppression system. NFPA *Standard* 92 suggests values of minimum and maximum design pressure difference.

Computer Analysis

CONTAM (Walton and Dols 2005) is the de facto standard computer program for analyzing pressurization smoke control systems. It is a network model that simulates airflow and contaminant flow in buildings. Network modeling for smoke control dates back to the 1960s, but these early models were subject to numerical difficulties and data input was extremely cumbersome and time consuming. CONTAM has superior numerical routines and sophisticated data input, and can be downloaded from the NIST web site (<http://www.bfrl.nist.gov/IAQanalysis/>) at no cost. Note that, when CONTAM is discussed in this chapter, other network models could be used instead.

Network models represent a building by a network of spaces or nodes, each at a specific pressure and temperature. The stairwells

and other shafts can be modeled by a vertical series of spaces, one for each floor. Air flows through leakage paths (e.g., doors or windows that may be opened or closed, partitions, floors, exterior walls, roofs) from regions of high pressure to regions of low pressure. Air-flow through a leakage path is a function of the pressure difference across the leakage path.

In network models, air from outside the building can be introduced by a pressurization system into any level of a shaft or into other building spaces. This allows simulating pressurization of a stairwell, elevator shaft, stairwell vestibule, and any other building space. In addition, any building space can be exhausted. This allows analysis of zoned smoke control systems where the fire zone is exhausted and other zones are pressurized. The pressures and flows throughout the building are obtained by solving conservation equations for the network. Analysis can include the driving forces of wind, the pressurization system, and indoor-to-outdoor temperature difference.

The primary purpose of network simulations is to determine whether a particular smoke control system in a particular building can be balanced such that it will perform as intended. Network models can simulate pressures and flows throughout very large and complicated building networks with high accuracy, although the results are approximations.

There are many flow paths in buildings, including gaps around closed doors, open doors, and construction cracks in walls and floors, and these flow paths are approximated for a design analysis. However, the approximated results can be useful in identifying problems with specific smoke control systems, so the smoke control system or the building can be modified appropriately. These simulations can also provide information to help size system components such as supply fans, exhaust fans, and vents.

First-time users of CONTAM may be confused by its extensive capabilities, many of which are not usually used for smoke control analysis. Chapter 14 of the *Smoke Control Handbook* has CONTAM user information intended to help start using the software for analysis of smoke control systems that rely on pressurization. This information includes a section on speeding up data input.

8. SHAFT PRESSURIZATION

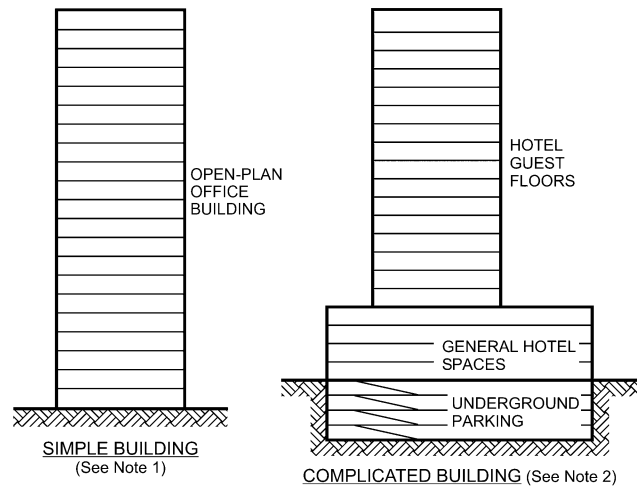
Stairwell pressurization and elevator pressurization are two kinds of shaft pressurization systems. Major factors that must be addressed in the design of these systems are building complexity and stack effect.

Building Complexity

Building complexity is a major factor in shaft pressurization, and successful shaft pressurization can be challenging in complicated buildings. A simple building has floor plans that are nearly the same from floor to floor, whereas a complicated building's floor plans differ considerably from floor to floor. Figure 9 shows examples of these buildings. Air leaving a pressurized shaft flows through the building to the outdoors, and flow paths to the outdoors differ by floor in complicated buildings. This results in varying pressure differences across pressurized shafts from floor to floor in complicated buildings, and can result in challenging shaft pressurization systems. Stairwell pressurization is usually straightforward for simple buildings, but elevator pressurization can be a challenge even in simple buildings. Systems that can be used to overcome these challenges are discussed in the sections on Pressurized Stairwells and Pressurized Elevators.

Stack Effect

Sometimes engineers will say that a pressurized stairwell or elevator must be designed to account for stack effect. If the space is properly pressurized, there is no neutral plane, and all the flows are from the stairwell. Strictly speaking, then, there is no stack effect in



Notes:

1. For smoke control purposes, a simple building is one where floor plans are nearly the same from floor to floor.
2. For smoke control purposes, a complicated building is one where floor plans differ considerably from floor to floor.

Fig. 9 Examples of Simple and Complicated Buildings

the pressurized stairwell or elevator: what is meant is that the space must be designed to account for the temperature differences that cause stack effect.

Caution: It is a myth that stack effect is the major factor affecting stairwell and elevator pressurization. Stack effect is a minor factor for most pressurized stairwells and elevators. Pressurization air for many stairwells and elevators is untreated outdoor air that is not heated or cooled. The temperature of these shafts is often nearly the same as the outdoor temperature, and the consequence of stack effect is significantly reduced as compared to shafts pressurized with air treated to the building temperature.

Shaft Temperature. When pressurization air is untreated, the shaft temperature can be expressed as

$$T_S = T_O + \eta(T_B - T_O) \quad (12)$$

where

- T_S = temperature in stairwell, °C
- T_O = temperature outdoors, °C
- T_B = temperature in building, °C
- η = heat transfer factor

There has been little research on the heat transfer factor, but it is believed to be in the range of 0.05 to 0.15. Without better data for a specific application, a heat transfer factor of 0.15 is suggested as conservative for the consequence of stack effect.

For untreated supply air, it takes a few minutes for the temperature in the shaft to stabilize near that of the outdoors. During this stabilization, excessive pressure differences could be produced. To prevent this, supply air can gradually be increased so that, when the shaft temperature is near that of the building, there is insufficient flow to cause excessive pressurization. If needed, temperature stabilization can be evaluated by a heat transfer analysis.

Friction Losses in Shafts. Pressure losses from friction in stairwells and elevator shafts can be significant when flow rates are high. CONTAM uses data from Achakji and Tamura (1988) and Tamura and Shaw (1976b) to calculate pressure loss in stairwells.

9. PRESSURIZED STAIRWELLS

Many pressurized stairwells have been designed and built to provide a tenable environment inside the stairwell in the event of a building fire. They also provide a smoke-free staging area for firefighters. On the fire floor, a pressurized stairwell is intended to provide a

positive pressure difference across a closed stairwell door to prevent smoke infiltration.

Air can be supplied to a pressurized stairwell at one or several locations. A **single-injection system** supplies pressurized air to the stairwell at one location, usually at the top. This system has the potential for smoke to enter the stairwell through the pressurization fan intake, so consider using automatic shutdown during such an event.

For tall stairwells, single-injection systems can fail when a few doors are open near the air supply injection point, especially in bottom-injection systems when a ground-level stairwell door is open.

Air can be supplied at multiple locations over the height of a tall stairwell. **Figures 10 and 11** show two examples of **multiple-injection systems** that can be used to overcome the limitations of single-injection systems. Multiple-injection systems can use one fan or multiple fans. When one fan is used, air is supplied through a duct that is usually in a separate duct shaft. However, some systems eliminate the expense of a separate duct shaft by locating the supply duct in the stairwell itself. In such a case, ensure that the duct does not obstruct orderly building evacuation.

Stairwell Compartmentation

Stairwell compartmentation, which is not often used, consists of dividing a stairwell into several sections consisting of five to ten stories each; each compartment has at least one supply air injection point. The compartments are separated by walls with normally closed doors. The main advantage of compartmentation is that it allows acceptable pressurization of stairwells that are otherwise too

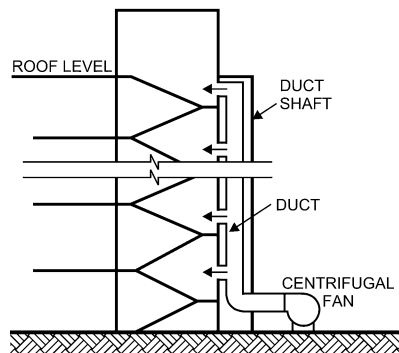


Fig. 10 Stairwell Pressurization by Multiple Injection with Fan Located at Ground Level

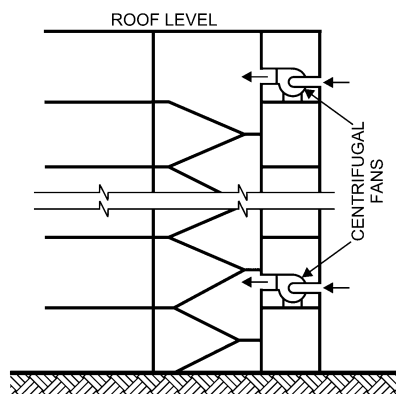


Fig. 11 Stairwell Pressurization by Multiple Injection with Multiple Fans

tall for acceptable pressurization. A disadvantage is the increase in floor area needed for the walls and doors separating the stairwell sections. When the doors between compartments are open, the effect of compartmentation is lost. For this reason, compartmentation is inappropriate for densely populated buildings, where total building evacuation by stairwell is planned in the event of a fire.

Vestibules

Pressurized stairwells with vestibules are occasionally used. The vestibules can be unpressurized, pressurized, ventilated, or both pressurized and ventilated. Vestibules provide an additional barrier around a stairwell, and can reduce the probability of an open-door connection existing between the stairwell and the building.

An evacuation analysis can determine the extent to which both vestibule doors are likely to be opened simultaneously. For densely populated buildings, it is expected that on many floors both vestibule doors would be opened simultaneously. Therefore, vestibules may provide little benefit of an extra barrier for densely populated buildings.

The algebraic equation method of analysis can be used to analyze a pressurized stairwell with an unpressurized vestibule. The pressure differences and flows of stairwell systems with any kind of vestibules, including those with openings to the outdoors and those with combinations of supply air and exhaust air, can be analyzed by CONTAM.

System with Fire Floor Exhaust

This system can achieve acceptable pressurization of tall stairwells in very complicated buildings. A relatively small amount of air is supplied to the stairs, and the fire floor is exhausted such that acceptable pressurization is maintained on the fire floor where it is needed. It is common to also exhaust one or two floors above and below the fire floor. Fire floor exhaust with stairwell pressurization is discussed further in the section on Zoned Smoke Control.

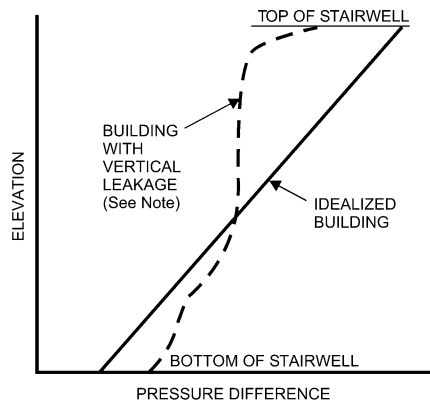
Analysis of Pressurized Stairwells

Pressure differences across a stairwell tend to vary over the height of the stairwell. **Figure 12** shows pressure profiles for pressurized stairwells in an idealized building (i.e., no vertical leakage through the floors and shafts, and leakage is the same from floor to floor) and in a more realistic building with vertical leakage through floors and an elevator shaft. This figure is for winter. When it is cold outdoors, the pressure differences tend to be less at the bottom of the stairwell than at the top. When it is hot outdoors, the trend is the opposite. For both winter and summer conditions, the pressure profile for an idealized building is a straight line.

The pressure profiles of stairs in real buildings depend on many factors, including (1) leakage values of the building components, (2) building floor plans, (3) size of elevator shaft or shafts and number of elevator doors, (4) presence or absence of elevator vents, and (5) leakage through other shafts. There are many possible shapes for such pressure profiles in real buildings.

For a building with vertical leakage, flows through the floors and shafts to some extent even out the highest and lowest pressure differences across the stairwell. The profile for a building with vertical leakage is bounded by the extremes of the pressure profile of the idealized building. This means that, other things being equal, the smallest pressure difference of the idealized analysis is less than that of the realistic building, and that the largest pressure difference of the idealized analysis is more than that of the realistic building. This is why the algebraic equation method discussed in the section on Equations for Steady Smoke Exhaust is conservative.

An algebraic equation method of analysis pressurized stairwells is also presented in Chapter 10 of the *Smoke Control Handbook*. This algebraic equation method is based on (1) the idealized building, (2) flows calculated by the orifice equation, (3) effective areas,



Note: Shape of curve for building with vertical leakage depends on many factors, and curve shown is only one of many possible shapes.

Fig. 12 Pressure Profile of a Pressurized Stairwell in Winter

Table 3 Stairwell Supply Air as Function of Leakage Classification

Stairwell Leakage Classification	Wall Leakage, m ² /m ²	Door Leakage, m ²	Supply Air, m ³ /(s·floor)
Low	1.4 × 10 ⁻⁵	0.0075	0.04
Average	1.1 × 10 ⁻⁴	0.015	0.11
High	3.5 × 10 ⁻⁴	0.022	0.26

Note: The supply air listed was calculated by equation method to maintain a minimum pressure difference of 25 Pa.

and (4) symmetry. It does not account for pressure losses in the stairwell from friction, but these losses tend to be small for stairwells when all stair doors are closed. CONTAM can analyze pressurized stairwells much more realistically than the algebraic equation method.

Stairwell Fan Sizing

Some designers size fans for pressurized stairwells using their own rules of thumb, which are generally in the range of 0.14 to 0.26 m³/s per floor. Such estimates can be appropriate for simple buildings such as those discussed previously. The primary factor regarding the amount of pressurization air needed is stairwell leakage. Table 3 lists the supply air needed to pressurize stairwells as a function of leakage classification. If the fan is oversized, the amount of supply air can be adjusted during commissioning to achieve successful pressurization. Because of the high cost of replacing undersized fans (including electrical wiring), rules of thumb chosen by designers usually incorporate an allowance for leakier construction than actually anticipated.

Height Limit

For some tall stairwells, acceptable pressurization may not be possible because of indoor-to-outdoor temperature differences. This is more likely with systems with treated supply air than those with untreated supply air.

The **height limit** is the height above which acceptable pressurization is not possible for an idealized building. For the height limit to be applicable to a building, all the floors of the building must be the same or relatively similar. When using the height limit, shafts that are not pressurized are neglected. For standard atmospheric pressure at sea level, the height limit is

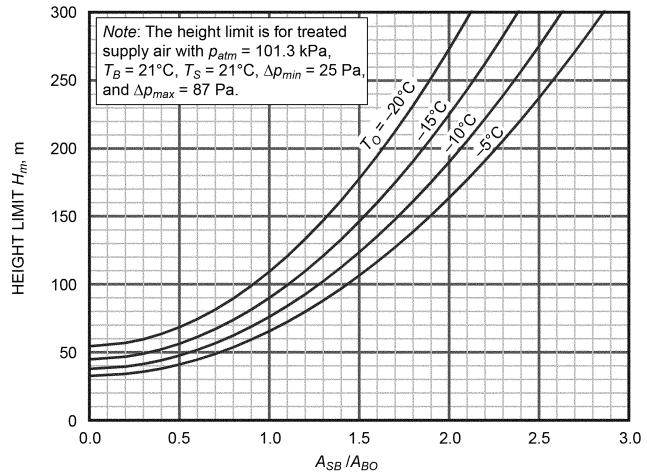


Fig. 13 Height Limit with Treated Supply Air in Winter

$$H_m = 2.89 \times 10^{-4} \frac{F_R (\Delta p_{max} - \Delta p_{min})}{\left| \frac{1}{T_o} - \frac{1}{T_S} \right|} \quad (13)$$

where

- H_m = height limit, m
- F_R = flow area factor
- Δp_{max} = maximum design pressure difference, Pa
- Δp_{min} = minimum design pressure difference, Pa
- T_o = absolute temperature outdoors, K
- T_S = absolute temperature in stairwell, K

The flow area factor is

$$F_R = 1 + \frac{A_{SB}^2 (T_B)}{A_{BO}^2 (T_S)} \quad (14)$$

where

- A_{SB} = flow area between stairwell and building, m²
- A_{BO} = flow area per stairwell between building and outdoors, m²
- T_S = absolute temperature in stairwell, K
- T_B = absolute temperature in building, K

Figure 13 shows the height limit calculated from Equations (13) and (14) for winter with treated supply air, and Figure 14 shows the same thing for winter with untreated supply air. The areas A_{SB} and A_{BO} are calculated using effective areas. The effective area of a system of flow areas is the area that results in the same flow as the system when it is subjected to the same pressure difference over the total system of flow paths. The effective area of any number of flow paths in parallel is

$$A_e = \sum_{i=1}^n A_i \quad (15)$$

and the effective area of any number of paths in series is

$$A_e = \left(\sum_{i=1}^n \frac{1}{A_i} \right)^{-1/2} \quad (16)$$

where

- A_e = effective area, m²
- A_i = flow area of path i , m²

Two examples (Figures 15 and 16) are used here to demonstrate evaluation of A_{SB} and A_{BO} . The areas on these figures include wall leakage through construction cracks or other paths, including gaps around doors, as appropriate for each section of wall. Figure 15 is a floor plan of a simplified open-plan office building. Because the height limit is based on symmetry, the area A_{BO} is on a per-stairwell basis. Figure 15 shows the axis of symmetry, and flows and flow paths on one side of this axis are the mirror image of those on the other side. This figure is geometrically symmetric, but the height limit also can be used for buildings where the building is only symmetric with respect to flow. In this figure, the areas between the building and the outdoors are A_1 , A_2 , and A_3 . These areas are in parallel, and based on Equation (15), $A_{BO} = A_1 + A_2 + A_3$. The areas between the stairwell and the building are A_4 and A_5 , which are also in parallel. Based on Equation (15), $A_{SB} = A_4 + A_5$.

The stairwells of Figure 16 have unpressurized vestibules. As with Figure 15, $A_{BO} = A_1 + A_2 + A_3$. Calculating A_{SB} involves flow areas both in parallel and in series. Equation (16) can only be used when no air is supplied to or exhausted from the spaces in the system of series paths. The effective area approach can be used because the only space in this path is an unpressurized vestibule. In Figure 16, the areas A_5 and A_6 are in parallel, so $A_{56} = A_5 + A_6$. The path through the vestibule is series, so from Equation (16), $A_{456} = (1/A_4^2 + 1/A_{56}^2)^{-1/2}$. The paths A_{456} and A_7 are in parallel, so $A_{SB} = A_{456} + A_7$.

Example 2. For the simple building of Figure 17, (1) evaluate wind effect, (2) evaluate stack effect, and (3) determine the design capacity of the

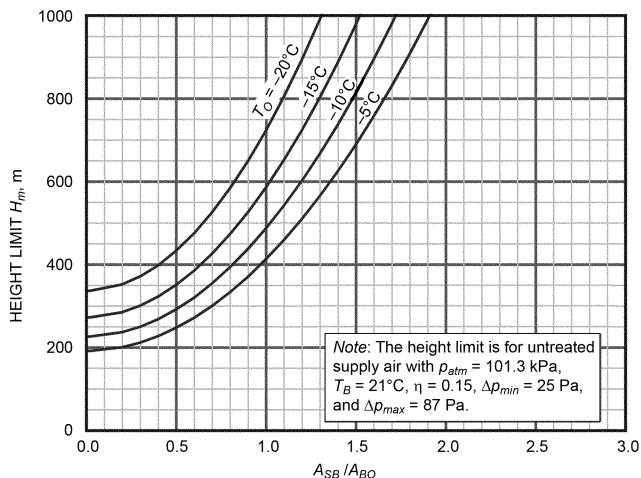
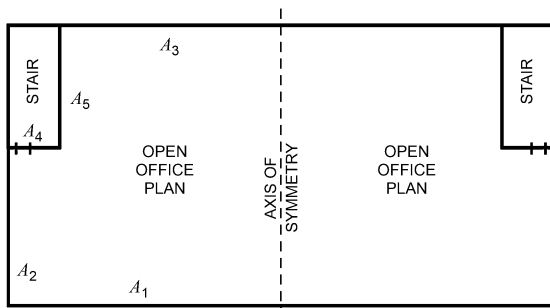


Fig. 14 Height Limit with Untreated Supply Air in Winter



Note: This figure is geometrically symmetric, but height limit can be used for buildings where building is only symmetric with respect to flow.

Fig. 15 Example for Effective Flow Areas of Building with Pressurized Stairwells

supply fans. The height of the building and stairwells is 33.5 m. The minimum and maximum design pressure differences are 25 and 87 Pa.

Wind Effect. For this building, wind effect is not considered to be an issue because

- There are no windows or balcony doors that can be opened between the building and the outdoors.
- A centrifugal fan is used to minimize wind effect on the flow rate of pressurization air. (Wind effect can also be minimized by other kinds of fans, although this requires evaluation for the specific case.)

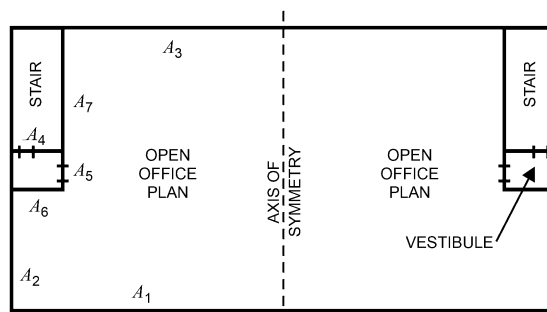
For designs where wind effect is not minimized, CONTAM is recommended for analyzing the stair pressurization system.

Stack Effect. The stairwells are pressurized with untreated air. Under these conditions, it takes a few minutes for stairwell temperature to stabilize. Stack effect can be a concern before and after temperature stabilization.

The winter outdoor design temperature is $T_o = -15^\circ\text{C}$, and the building temperature is $T_B = 21^\circ\text{C}$. The atmospheric pressure is 101.3 kPa. Consider a heat transfer factor of $\eta = 0.15$. Because the building is simple, height limit can be used to evaluate stack effect. First, evaluate stack effect before stabilization; the first approach for this is to examine the height limit for the stairwell if pressurization air were treated. From Figure 14 with $T_o = -15^\circ\text{C}$, the smallest value of height limit is about 45 m when A_{SB}/A_{BO} is near zero. The stairwell height is 33.5 m, which is less than the height limit. This means that stack effect is not an issue before temperature stabilization; consequently, it cannot be an issue after stabilization.

Size Supply Fans: Because this building is simple, the rule of thumb method can be used to size the fans. Generally, rules of thumb for pressurized stairwells are in the range of 0.14 to 0.26 m^3/s per floor. The most important factor to consider in choosing a rule of thumb is the stairwell leakage, which primarily consists of the leakage of stairwell walls and stairwell doors.

Construction of the stairwell is believed to be of average leakiness or higher. Table 3 lists supply air of 0.11 m^3/s per floor for average leakage, and 0.26 m^3/s per floor for high leakage. Because of the cost of replacing an undersized fan, the rule of thumb of 0.21 m^3/s per floor



Note: This figure is geometrically symmetric, but height limit can be used for buildings where building is only symmetric with respect to flow.

Fig. 16 Example for Effective Flow Areas of Building with Pressurized Stairwells and Unpressurized Vestibules

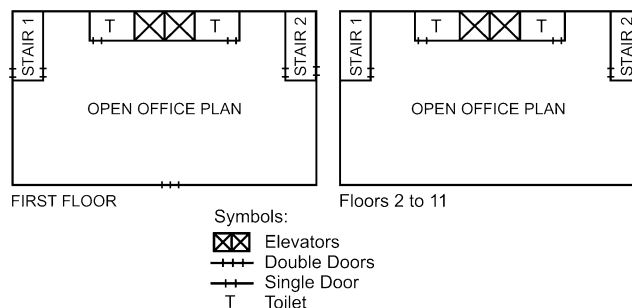


Fig. 17 Office Building of Stairwell Examples

is chosen. The stairwell has 11 floors, and fan capacity is $11(0.21) = 2.31 \text{ m}^3/\text{s}$. Each stairwell is pressurized by one fan with capacity of $2.31 \text{ m}^3/\text{s}$.

Stairwells with Open Doors

When any stair door is opened in a simple stairwell pressurization system, the pressure difference drops significantly. When all doors are closed suddenly in such a simple system, the pressure difference increases significantly. A **compensated stairwell pressurization system** adjusts for changing conditions either by modulating supply airflow or by relieving excess pressure. The intent is to maintain acceptable pressurization when doors are opening and closing.

In the United States, most codes do not require pressurized stairwells to be compensated, and such stairwells are designed to maintain pressurization only when all the stair doors are closed. Traditionally, some engineers felt that pressurized stairwells needed to be compensated, but an incidental finding of a study by Klote (2004) casts doubt on this opinion. For two simulations in this study with a closed stair door on the fire floor and some other stair doors open, the stairwell remained tenable because smoke that leaked into the stairwell was diluted by the large amount of air supplied to the stairwell. In light of this finding, ASHRAE is sponsoring research project RP-1447 to study the need for compensated stair systems.

Many kinds of compensated stairwell pressurization systems have been used, but the most common are the open exterior door system and the variable-air-volume (VAV) system. The **open exterior door system** has constant-supply airflow, and an exterior stairwell door that opens automatically upon system activation. This system is sometimes called the **Canadian system**, because it originated in Canada and has been used extensively there. The supply air rate is not actually constant, but it varies to some extent with pressure across the fan. For centrifugal fans, this flow variation is generally small. However, the phrase “constant supply” is used to differentiate this system from those where the supply air intentionally changes.

By eliminating opening and closing of the exterior stairwell door during system operation, the Canadian system eliminates the major source of pressure fluctuations. This system is simple and relatively inexpensive, but there are many locations where opening exterior doors automatically raises issues of building security. For complicated buildings, a CONTAM analysis of this system is recommended to ensure that it operates as intended.

With the **VAV system**, the flow rate of supply air to the stairwell is adjusted to account for opening and closing of doors. Tamura's (1990) research on VAV systems at the National Research Council of Canada found that the pressure dropped when doors were opened, and it took about 3 to 7 min to recover to the initial pressure. When all the stair open doors in a VAV system are closed, there is a pressure spike, which Tamura found had a peak of 181 Pa. This spike only lasted about 30 or 40 s, but the peak was much more than any reasonable maximum design pressure difference. Such peaks are a concern. Occupants encountering such a peak would probably not be able to open the stair door, but they could open it a minute or so later; however, it is possible that a person encountering such a peak would think the stair door was locked, and might not try to open it again.

Wind can have a significant effect on VAV stair pressurization systems. During design analysis of some of these systems, some engineers have encountered very high pressure differences during some wind conditions. For example, when an exterior door is opened during the design wind speed, a compensated stair system may supply so much air that the pressure difference across some stair doors may exceed the maximum design value by as much as 100%. During such an occurrence, it would be impossible or extremely difficult for occupants to enter the stairwell. For this reason, it is recommended that design analysis of VAV compensated

stairwell pressurization systems include CONTAM simulations under wind conditions.

10. PRESSURIZED ELEVATORS

The elevator pressurization systems discussed in this section are intended to prevent smoke from flowing from the fire floor through an elevator shaft and threatening life on floors away from the fire floor. This section does not address smoke control for elevator evacuation (see Chapter 12 of the *Smoke Control Handbook*). Usually, pressurized elevators are in buildings that have pressurized stairwells, and this section assumes that these pressurization systems operate together. In the rare situation where pressurized elevators are the only pressurization smoke control system in a building, the information in this section may still be useful.

The information discussed in the section on Elevator Piston Effect can be used to evaluate the influence of piston effect on performance of pressurized elevator systems. The piston effect produces a pressure spike when a car passes a particular floor, and this happens for only a few seconds during the run of an elevator. For elevators in multiple-car shafts with car velocities less than 5 m/s, or for those in single-car shafts with car velocities less than 2.5 m/s, piston effect should not adversely affect performance of elevator pressurization.

Design of pressurized elevators is much more complicated than design of pressurized stairwells, because (1) the building envelope often cannot effectively handle the large airflow resulting from both elevator and stairwell pressurization, and (2) open exterior doors on the ground floor can cause high pressure differences across the elevator shaft at the ground floor. Several systems can deal with this complexity, however.

Usually, several exterior doors on the ground floor are open during a building fire: the fire service opens several exterior doors and keeps them open while fighting the fire. Occupants also open exterior doors during evacuation. The shaft pressurization system needs to operate as intended with these exterior doors open.

Generally, a CONTAM analysis is needed to determine whether pressurized elevators and pressurized stairwells in a particular building can be balanced to perform as intended. Though it is theoretically possible to use only a rule of thumb to design these systems, a CONTAM analysis is strongly recommended.

The following discussion is intended to provide an understanding about the elevator pressurization systems, and is based on 36 CONTAM simulations with a 14-story building (Figure 18). For a more detailed discussion of these simulations, see Chapter 11 of the *Smoke Control Handbook*. Elevator pressurization systems discussed here are for use in buildings with pressurized stairwells.

For these simulations, the pressure difference criteria are listed in Table 4. The leakage values and flow coefficients used for these simulations are listed in Tables 5 and 6. For the CONTAM simulations of the example building, supply air was injected only at the top of the elevator shafts, but about half the supply air was injected at the top of the stairs and the rest at the second floor.

Basic System

In the basic system, each stairwell and elevator shaft has one or more dedicated fans that supply pressurization air. For reasons mentioned previously, the basic system also includes stairwell pressurization, and the stair subsystems are not compensated. In most buildings, the basic system does not result in successful pressurization, so the systems discussed in this section add extra features to improve performance.

For the example building with very leaky exterior walls, the CONTAM simulations showed that the basic system would perform well, but this was not so for with less leaky exterior walls. In Figure 19, for leaky exterior walls, the pressure difference across

the elevator doors on the ground floor is about 130 Pa. For exterior walls of average leakage, the pressure difference across the elevator doors on the second floor is about 87 Pa, and at the ground floor it is about 470 Pa. These values exceed the maximum criterion used for elevator doors, which is 62 Pa (see Table 4). For average and leaky exterior walls, there is insufficient leakage in the building envelope to accommodate the large amount of pressurization air supplied to the shafts.

With very leaky exteriors walls, Figure 19 shows that the basic system meets the pressure difference criteria (Table 4). Air was supplied to each elevator shaft at 13.1 m³/s, and air was supplied to each stairwell at 3.09 m³/s. With very leaky exteriors walls, there is enough wall leakage area to accommodate this large amount of pressurization air. For the few buildings that have very leaky building envelopes, the basic system can be a simple way to pressurize

elevators and stairwells. For less leaky buildings, consider the systems discussed in the following sections.

Exterior Vent (EV) System

This system uses vents in the exterior walls to increase the leakiness of the building envelope such that successful pressurization can be achieved. The vents are usually closed, but they open when the pressurization system is activated. Vents should be located in a manner to minimize adverse wind effects, and supply intakes must be located away from the vents to minimize the potential for smoke feedback into the supply air. These vents may need fire dampers, depending on code requirements.

Figure 20 is a typical floor of the example building with vents in the exterior walls. Vents can be sized to ensure the design criteria are met. In the example building, the vents were sized such that the amount of pressurization used for the basic system produced acceptable pressurization with the EV system in the example building.

Table 4 Pressure Differences Criteria for Elevator Pressurization Simulations, Pa

System	Minimum	Maximum
Pressurized elevators	25	62
Pressurized stairwells	25	87

Note: Criteria are for elevator simulations discussed in this chapter, but some projects may have different criteria, depending on code requirements and requirements of specific applications.

Table 5 Flow Areas and Flow Coefficients of Doors Used for Elevator Pressurization Simulations

Flow Path	Flow Coefficient	Flow Area, m ²
Single door, closed	0.65	0.023
opened	0.35	2.0
Double door, closed	0.65	0.045
opened	0.35	3.9
Elevator door, closed	0.65	0.06
opened	0.65	0.56

Note: Values were chosen for elevator simulations discussed in this chapter; flow areas and coefficients appropriate for design analysis of a specific building may be different.

Table 6 Flow Areas and Flow Coefficients of Leakages Used for Elevator Pressurization Simulations

Flow Path	Leakage Classification	Flow Coefficient	Flow Area, m ² per m ² of wall
Exterior walls	Tight	0.65	0.50 × 10 ⁻⁴
	Average		0.17 × 10 ⁻³
	Loose		0.35 × 10 ⁻³
Interior walls	Very loose		0.12 × 10 ⁻²
	Loose	0.65	0.35 × 10 ⁻³
	Tight	0.65	0.66 × 10 ⁻⁵
Floor or roof	Average		0.52 × 10 ⁻⁴
	Loose		0.17 × 10 ⁻³
Curtain wall gap	Tight	0.65	0.00061
	Loose		0.0061

Note: Values were chosen for elevator simulations discussed in this chapter; flow areas and coefficients appropriate for design analysis of a specific building may be different.

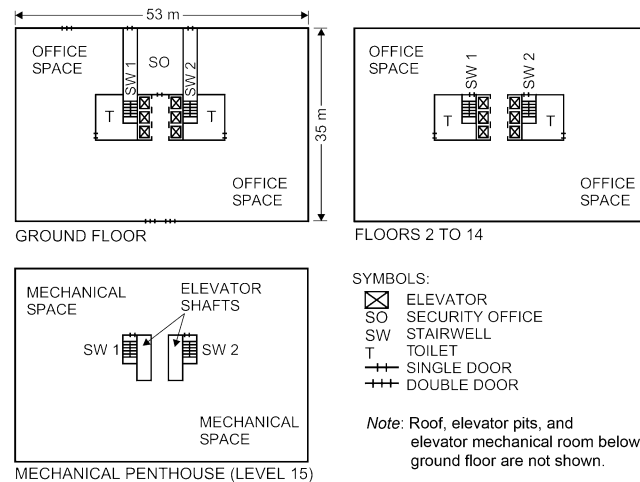


Fig. 18 Floor Plans of the Example 14-Story Open Plan Office Building for Elevator Pressurization Study

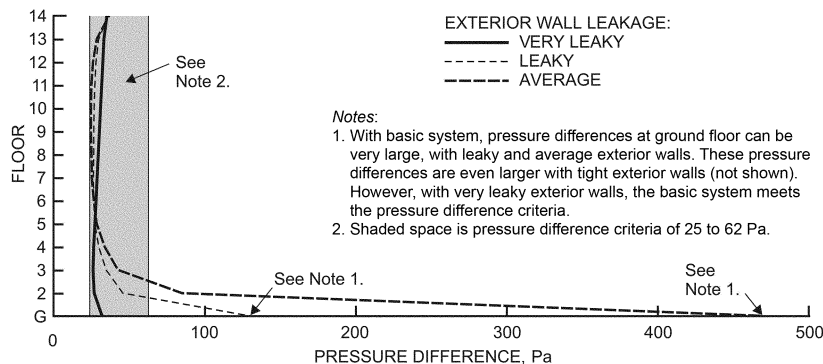


Fig. 19 Elevator Pressure Differences for Basic Elevator Pressurization System

In Figure 20, the vents are in all four exterior walls to minimize any adverse effects of wind. The vent area should be proportional to the area of the exterior walls. If fewer vents are used, wind effects should be incorporated in the CONTAM analysis.

With open exterior doors, it is not necessary to have exterior vents on the ground floor. Because the EV system may not be able to achieve acceptable pressurization with some or all the exterior doors closed, it may be necessary to have some of the exterior doors open automatically on system activation. The number of exterior doors that need to open automatically can be evaluated by the CONTAM analysis.

The example building has an open office plan, but the EV system can be adapted to other buildings. Ducted flow paths can be installed from the vicinity of the unenclosed elevator lobbies to the outdoors. Such ducted paths can overcome the flow resistance of interior walls. The ducts can be located above suspended ceilings. Duct penetrations of a fire-rated wall may have fire resistance requirements, depending on code specifications.

Floor Exhaust (FE) System

The FE system is a kind of zoned smoke control that reduces the amount of supply air used. In the FE system, a relatively small amount of air is supplied to the elevator shafts and the stairwells, and the fire floor is exhausted such that acceptable pressurization is maintained on that floor where it is needed. It is common to also exhaust one or two floors above and below the fire floor.

As discussed in the section on Zoned Smoke Control, exhausting air from the fire floor and some floors above and below the fire floor benefits shaft pressurization. Often, this system can achieve successful pressurization in tall and very complicated buildings.

Typically, exhaust is through a shaft with a fan located in a mechanical floor or on the roof, and dampers between the shaft and the floors are closed on all floors when the system is not operating. On system activation, the dampers open on the floors to be exhausted. The outlet of the exhaust fan must be located away from the inlets of the supply fans to minimize the potential for smoke feedback into supply air.

As with the EV system, some of the exterior doors on the ground floor may need to open automatically upon system activation, and the number of such doors can be evaluated by the CONTAM analysis.

For the example building, an FE system is shown in Figure 21. Simulations showed that each elevator shaft needed 7.14 m³/s, and each stairwell needed 1.79 m³/s. The floor exhaust needed from the floors ranged from 2.28 to 2.55 m³/s.

As with the EV system, the FE system can be adapted to other buildings. This can be done by having the exhaust draw from a space onto which the elevators and stairwells open.

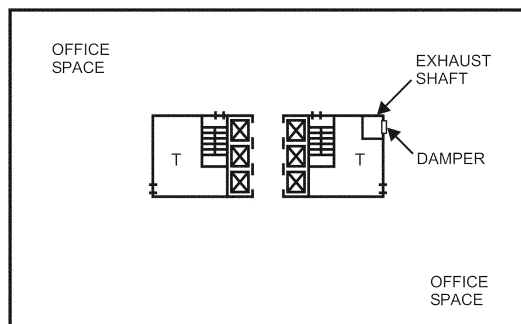
Ground-Floor Lobby (GFL) System

This system has an enclosed elevator lobby on the ground floor to reduce the tendency of open exterior doors to cause high pressure differences across the elevator shaft at the ground floor. The GFL system often has a vent between the enclosed lobby and the building to prevent excessive pressure differences across the lobby doors (i.e., the doors between the enclosed lobby and the building).

The pressure difference across the lobby door and the elevator door depends on the area of the vent. There is no established criterion for the maximum pressure difference across the lobby doors, but the pressure should not be high enough to prevent the doors from remaining closed. This value depends on the specific doors and hardware. This discussion uses a maximum pressure difference for the lobby doors of 87 Pa, but this value can be much different for specific applications. The vent should have a fire damper and a control damper in series. The control damper can be used to adjust the flow area of the vent so it can be balanced during commissioning. Figure 22 shows the ground floor of the example building with a GFL system.

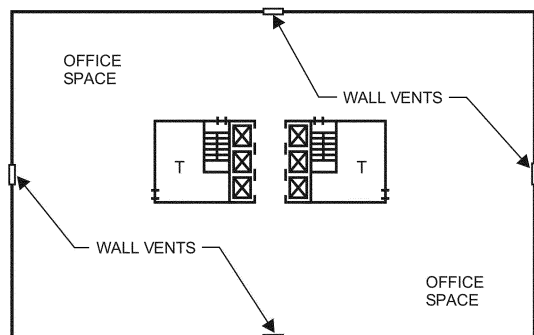
The intent of the elevator pressurization systems discussed in this chapter is to prevent smoke from flowing from the fire floor through an elevator shaft and threatening life on other floors. In the GFL system, the enclosed lobby on the ground floor protects the elevator from smoke from a fire on the ground floor. Thus, the minimum elevator pressure difference criterion of Table 4 does not apply to the ground floor for a GFL system. Table 7 lists the criteria that are used for the GFL system simulations. Successful pressurization consists of meeting these criteria.

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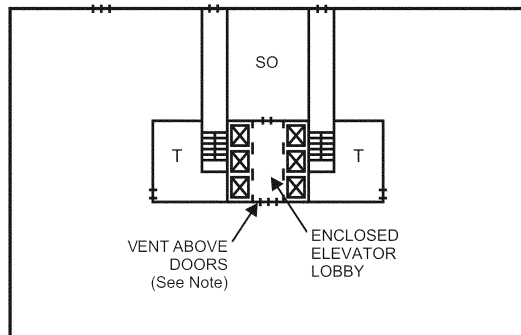
Note: Exhaust shaft has fan (not shown) located in mechanical penthouse, and dampers are closed on all floors when system is not operating. On system activation, dampers open on floors to be exhausted, and fan is activated.

Fig. 21 Typical Floor Plan of Example Building with Floor Exhaust (FE) System



Note: Vents open when elevator and stairwell pressurization is activated.

Fig. 20 Typical Floor Plan of Example Building with Exterior Vent (EV) System



Note: This vent needs fire damper and adjustable damper for balancing.

Fig. 22 Ground Floor of Building with Ground-Floor Lobby (GFL) System

Table 7 Pressure Differences Criteria for GFL Elevator Pressurization Simulations, Pa

Location	Minimum	Maximum
Pressurized elevators on ground floor	N/A	62
on other floors	25	62
Pressurized stairwells on all floors	25	87
Ground-floor elevator lobby door	N/A	87

Note: These pressure differences are with doors to stairwell, elevator, and ground-floor lobby closed. Criteria are for GFL simulations discussed in this chapter, and some projects may have different criteria depending on code requirements and requirements of specific applications.

For fires in high-rise buildings, the fire service frequently uses the elevators for rescue and for mobilization of firefighting equipment. When ground-floor lobby doors are opened, the pressure difference may exceed the maximum pressure difference. If this can happen for a particular design, the fire service should be contacted to determine whether this is acceptable to them.

The floor-to-floor leakage can significantly affect a GFL system's performance. This leakage consists of the leakage of the floor and that of the curtain wall gap (Table 6).

11. ZONED SMOKE CONTROL

The traditional approach for HVAC systems is to shut them down during building fires, but HVAC systems can be operated in smoke control mode during building fires. Zoned smoke control consists of exhausting the zone of the fire and possibly pressurizing the surrounding zones. In addition to using the HVAC system, dedicated equipment can be used for zoned smoke control.

In zoned smoke control, a building is divided into several zones, each separated from the others by barriers. In the event of a fire, the zone with the fire is called the **smoke zone**, and the others are called the **nonsmoke zones**. Zones bordering on the smoke zone are called the **surrounding zones**. Either passive or pressurization smoke protection is used to limit smoke spread beyond the smoke zone. Smoke control cannot make conditions tenable in the smoke zone, and occupants should evacuate the smoke zone as soon as possible.

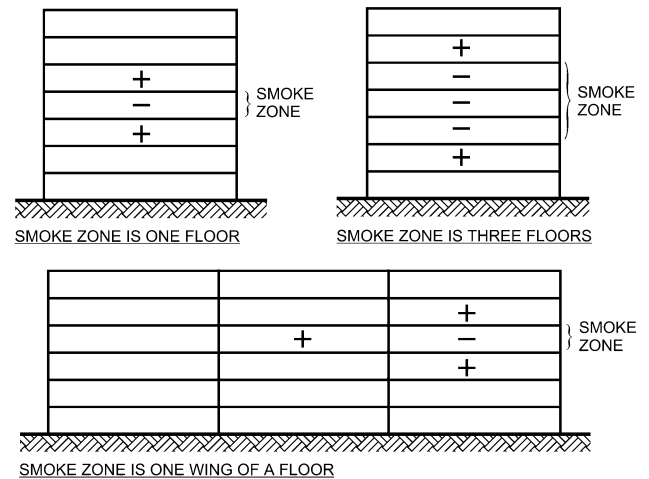
Some arrangements of smoke control zones are shown in Figure 23. In this figure, the smoke zone is indicated by a minus sign, and the surrounding zones are indicated by a plus sign. The smoke zone is often one floor of the building, but it can be the fire floor plus the floors directly above and below the fire floor. In a relatively low, sprawling building with several wings, the smoke zone can be part of a floor.

When separate HVAC systems serve each zone, systems distant from the smoke zone and surrounding zones should only remain operating if the building pressurization produced by these systems does not adversely impact zoned smoke control system performance. Otherwise, they should be shut down.

The traditional approach to zoned smoke control is to exhaust the smoke zone and to pressurize the surrounding zones, but other approaches have been used. Although fan-powered smoke exhaust is the most common method of treating the smoke zone, passive smoke control using smoke barriers may be satisfactory when fan-powered exhaust is not practical. Using exterior wall vents or smoke shafts to treat the smoke zone is not common, but these methods are discussed in Chapter 13 of the *Smoke Control Handbook*.

Fan-powered pressurization or passive smoke control using smoke barriers can be used for the zones surrounding the smoke zone. Fan-powered pressurization of the surrounding zones has a negative consequence on stairwell pressurization, as discussed in the following sections. In this section, fan-powered pressurization is called pressurization, and fan-powered exhaust is called exhaust.

When the floors or wings of a building are divided into many rooms with normally closed doors, these floors do not lend themselves to the traditional concept of zoned smoke control. For such



Notes:

1. In these figures, smoke zone is indicated by minus sign (-), and surrounding zones are indicated by plus sign (+).
2. Smoke zone can be treated by fan-powered exhaust or passive smoke control using smoke barriers.
3. Surrounding zones can be treated by fan-powered pressurization or passive smoke control using smoke barriers.

Fig. 23 Some Arrangements of Smoke Control Zones

applications, a form of zoned smoke control can be used that relies on a combination of corridor exhaust and passive smoke control using smoke barriers. The passive protection tends to minimize smoke flow through the ceiling floor assembly during building fires. Some applications suitable for such an approach are hotel guest floors, apartment buildings, and some office buildings.

Interaction with Pressurized Stairs

The interaction of zoned smoke control with pressurized stairwells can have a significant effect on pressure differences across the stairwell doors. The following discussion is about smoke zones that are one floor and surrounding zones consisting of one floor above and one floor below. However, the same kind of interactions can happen with smoke zones and surrounding zones that are more than one floor.

The interaction between zoned smoke control and pressurized stairwells is illustrated in Figure 24. For zoned smoke control using both exhaust and pressurization, pressurization of the surrounding zones decreases the pressure difference Δp_{SB} across pressurized stairwell doors on these floors. This decreased pressure difference can result in a failure mode of the pressurized stairwells on the floors being pressurized. However, this failure mode is eliminated by the use of zoned smoke control that uses exhaust only.

Ideally, exhaust and pressurization zoned smoke control should prevent smoke from reaching the floor above the smoke zone, and negative stairwell pressurization should not compromise tenability of the stairwell. The effectiveness of this depends on proper identification of the fire floor. Properly maintained fire alarm systems are very good at identifying the location of a fire, but no system is perfect. In some fires, the first smoke detector to activate was a floor or so above the fire floor. This can be attributed to any of the following: (1) smoke flowing through a complex route to a floor above the fire, (2) smoke detectors not working properly on the fire floor, and (3) signals from smoke detectors being misidentified.

Regardless of the reason, when a fire floor is incorrectly identified, the smoke zone is incorrectly chosen. In this situation, the failure mode is that inadvertent pressurization of the fire floor can push smoke into the stairwells (probably into all stairwells serving the fire floor). This failure mode is more of a concern for tall buildings

because acceptable pressurization is more difficult in tall buildings than in short ones, and stairwell smoke protection is more important in tall buildings (i.e., those with 10 or more stories) than in short ones. Occupant density is another factor affecting the importance of stairwell smoke protection. Because of this failure mode, it is recommended that zoned smoke control using systems using both exhaust and pressurization not be used for tall buildings where protection of the stairwells is especially important. Alternatively, analyze this failure mode, including factors such as evacuation time, emergency response time, and probability of using the firefighter's smoke control station (FSCS) for corrective action.

12. ATRIUM SMOKE CONTROL

Because of the lack of compartmentation in large-volume spaces, smoke protection for such spaces is important. This chapter considers a large-volume space to be at least two stories high, such as an atrium, exhibition center, enclosed shopping mall, arcade, sports arena, or airplane hangar.

For simplicity, the term **atrium** is used generically here to mean any of these large spaces.

Most atrium smoke control systems are designed to prevent exposure of occupants to smoke during evacuation; this is the approach described in this section. An alternative goal is to maintain tenable conditions even when occupants have some contact with smoke, as discussed in the section on Tenability Systems.

The following approaches can be used to manage smoke in atriums:

- **Smoke filling.** This approach allows smoke to fill the atrium space while occupants evacuate the atrium. It applies only to spaces where the smoke-filling time is sufficient for both decision making and evacuation. For information about people movement and evacuation time, see Chapter 4 of the *Smoke*

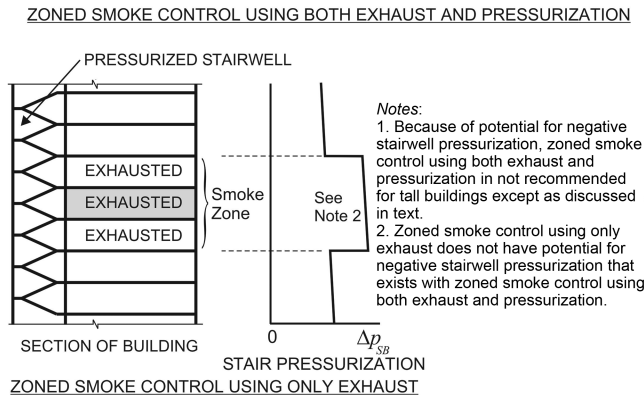
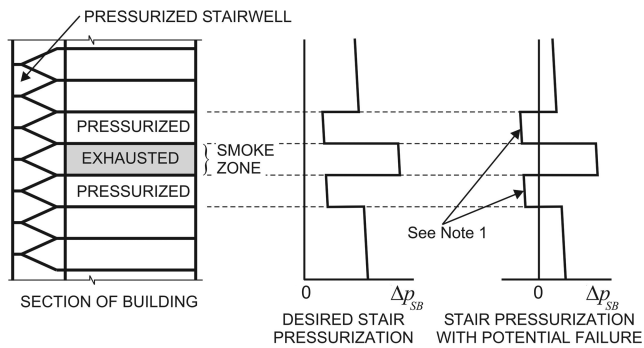


Fig. 24 Interaction Between Zoned Smoke Control and Pressurized Stairwells

Control Handbook. The filling time can be estimated either by zone fire models or by Equations (15.1) and (15.2) in the *Smoke Control Handbook*.

- **Unsteady smoke exhaust.** This approach exhausts smoke from the top of the atrium at a rate such that occupants have sufficient time for decision making and evacuation. It requires analysis of people movement and fire model analysis of smoke filling.
- **Steady smoke exhaust.** This approach exhausts smoke from the top of the atrium to achieve a steady clear height for a steady fire (Figure 25). A calculation method is given in the section on Equations for Steady Smoke Exhaust.

Design Fires

Analysis of the design fire is extremely important for atrium smoke control design, and an understanding of fire development is needed for such analysis. The intent of this section is to provide preliminary information of these topics. For more complete information, see Chapter 5 of the *Smoke Control Handbook*. By nature, fire is an unsteady process, but many design fires are steady fires. One of the most important aspects of a design fire is the **heat release rate (HRR)**.

When steady design fires are based on test data, it is accepted that HRR of the steady fire is taken as the maximum HRR of the test data. For example, the HRR of upholstered furniture from test data is shown in Figure 26. For a sofa, the HRR grows to a maximum of about 3200 kW, then decreases as the fuel burns out. A sofa design

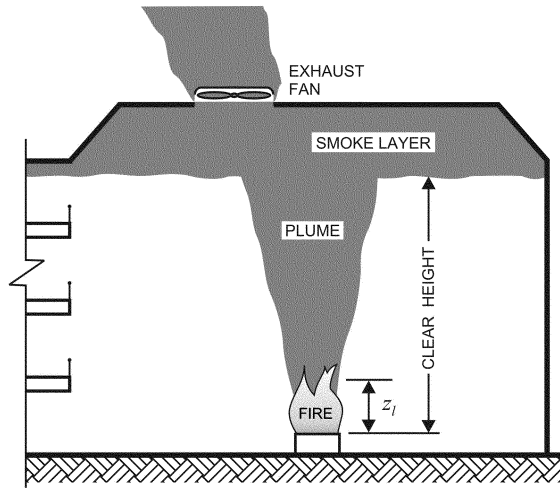


Fig. 25 Atrium Smoke Exhaust

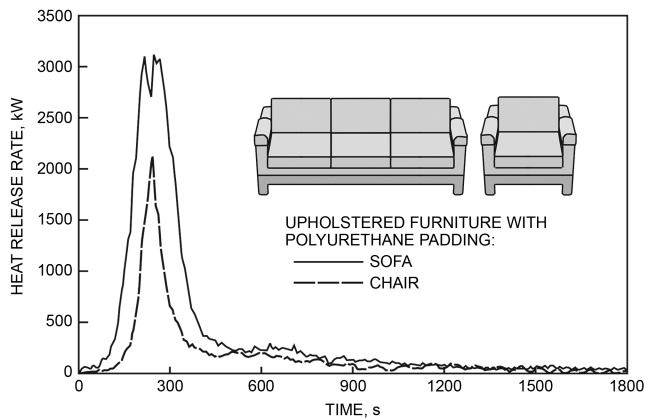


Fig. 26 HRR of Upholstered Sofa and Chair

fire could be unsteady based on the fire test data, or it could be a steady 3200 kW.

A design scenario is an outline of events and conditions that are critical to determining the outcome of alternative situations or designs. In addition to the fire location and HRR, it may include many other conditions such as materials being burned, outdoor temperature, wind, status of the HVAC system, and doors that are opened and closed.

A design analysis should include several design scenarios to ensure that the smoke control system will operate as intended. It is possible for an atrium project to have only one scenario, but most projects have two or three, and some complex projects require five or more.

Fire Development

The stages of fire development are useful when discussing fires. These stages are (1) growth, (2) flashover, (3) fully developed fire, and (4) decay. Not all fires go through all the stages, primarily because of a lack of fuel or fire suppression.

The growth stage follows ignition, and the early part of the growth stage is characterized by an abundance of air for the fire. During the growth stage, the fire often spreads from one object to another. The growth stage of a sofa fire is from ignition to the peak HRR of about 3200 kW. The growth stage is often characterized by the following equation:

$$q = 1000 \left(\frac{t}{t_g} \right)^2 \quad (17)$$

where

$$\begin{aligned} q &= \text{heat release rate, kW} \\ t &= \text{time, s} \\ t_g &= \text{growth time, s} \end{aligned}$$

Such a growth stage is called a **t-squared fire**, and typical growth times are listed in Table 8.

The development of a room fire in the growth stage may seem gradual. Smoke rises above the fire to form a smoke layer under the ceiling. Typically, the fire spreads from object to object, while the temperature of the smoke layer increases.

Flashover is a rapid change from a growth-stage fire to a fully developed fire, and primarily occurs by thermal radiation. This radiation is from the flames, the smoke plume and the hot smoke layer below the ceiling. Thin, easy-to-ignite materials (newspapers, draperies, etc.) near the fire are the first to burst into flame, and this is followed by ignition of the rest of the flammable materials in the room.

In a room with a fully developed fire, everything that can burn is burning. A fully developed fire also is called a **ventilation-controlled fire**, because the HRR depends on the amount of air that reaches the fire. During a fully developed fire, flames generally extend from the doorways or open windows of the fire room. A fully developed fire is characterized by inefficient combustion resulting in high carbon monoxide production. For a fully developed fire in room with one opening, the HRR within the fire room can be expressed as

$$q = 1260 A_w H_w^{1/2} \quad (18)$$

where

$$\begin{aligned} q &= \text{heat release rate of fully developed fire, kW} \\ A_w &= \text{area of ventilation opening, m}^2 \\ H_w &= \text{height of ventilation opening, m} \end{aligned}$$

For example, a fully developed fire in a room with a single door 1.07 by 2.13 m has an HRR of 4190 kW. The decay stage is a decrease in the HRR, which results from either fuel consumption or fire suppression. As the fuel is consumed, the fire may change from ventilation controlled to fuel controlled.

Table 8 Typical Fire Growth Times

t-Squared Fire	Growth Time t_g , s
Slow	600
Medium	300
Fast	150
Ultrafast	75

Note: Growth times from NFPA Standards 92 and 204.

Sprinklers

Sprinklers are used extensively because they effectively suppress fires. The possible responses to sprinkler spray include (1) HRR decay, (2) constant HRR, or (3) an increase in HRR. The first two responses might be considered successful suppression, but in the third case, the sprinkler spray is overpowered by the fire.

Sprinkler actuation depends on the temperature and velocity of the gases flowing by the sprinkler and on the responsiveness of the sprinkler. The responsiveness of a sprinkler is characterized by the **response time index (RTI)**. In a fire, a ceiling jet of hot gases flows in a radial direction from where the smoke plume contacts the ceiling. The RTI of standard-response sprinklers is greater than or equal to $80 \text{ m}^{1/2} \cdot \text{s}^{1/2}$, and the RTI of fast-response sprinklers is equal to or less than $50 \text{ m}^{1/2} \cdot \text{s}^{1/2}$. Computer programs can use the RTI and correlations for the ceiling jet to predict sprinkler actuation time, and some zone fire models (including CFAST, discussed in the section on Zone Fire Modeling) have this ability.

In spaces with high ceilings, the temperature of the smoke plume can drop so much that sprinklers may not activate, or activation may be so delayed that the spray can evaporate before it reaches the fire. Sprinklers in an atrium could have some beneficial effect, but for design purposes they are considered not effective in an atrium. However, they are usually considered effective for fires in communicating spaces (i.e., a space with an open pathway to an atrium, such that smoke from a fire in either the atrium or the communicating space can move from one to the other without restriction). Fires in communicating spaces are often included in design scenarios.

Shielded Fires

A fire can be shielded from the sprinkler spray if an obstruction is between the sprinkler and the fire. Not only does the obstruction shield the fire from the water spray, but it also prevents the usual formation of a smoke plume. Because the smoke plume of a shielded fire can be very different from that of an unshielded fire, the sprinkler actuation time of shielded fires must not be calculated by the computer methods mentioned previously.

Two models have been developed for the HRR of shielded fires, based on test data. At NIST, fire tests were based on a few field observations of fuel loadings in office buildings (Madrzykowski and Vettori 1992), with a peak HRR of shielded fires of 500 kW. At the National Research Council of Canada (NRCC), fire tests were based on extensive field observations of fuel loadings in many buildings (Lougheed 1997), with a peak HRR of shielded fires of 1000 kW.

A peak HRR of 1000 kW is suggested for most shielded fires, and an HRR of 500 kW for locations where fuel is limited, such as in a showplace office of the president of a large corporation.

Transient Fuels

Transient fuels are materials that are in a space temporarily. Examples include seasonal decorations, paint and solvents in stairwells during redecorating, unpacked foam cups in cardboard boxes after delivery, cut-up cardboard boxes awaiting removal, upholstered furniture after delivery, and stacked folding chairs. Sometimes, transient fuels remain in place for long periods: for instance, polyurethane mattresses delivered to a dormitory and waiting for

distribution in the next school year, automobiles on display in a shopping mall, boats and campers on display in an arena, or a two-story wood frame house built for display inside a shopping mall.

Transient fuel is likely to accumulate at most locations in a building, except where it would block the usual paths of heavy traffic. It is unlikely that a commonly used building entrance or corridor would be blocked by transient fuel, but there could be accumulations next to a wall near the entrance or in the corridor.

Location can play a key role in transient fuels. Consider a sofa with polyurethane foam padding that is delivered for the office of the corporate president. Because the sofa is new and clean, it is decided to temporarily leave it in the nearby atrium until it can be moved to the president's office. In a corridor of an office building, the fuel could be trash consisting of any number of things such as an old upholstered chair or cardboard boxes with packing materials.

Suggested Fire Sizes

In many atriums, fuel loading is severely restricted with the intent of restricting fire size. Such atriums are characterized by interior finishes of metal, brick, stone, or gypsum board and furnished with objects made of similar materials, plus plants. In this chapter, a heat release rate per floor area of 225 kW/m² is used for a fuel-restricted atrium, and 500 kW/m² is used for atriums containing furniture, wood, or other combustible materials. These heat release rates per unit floor area are from Morgan (1979) and Morgan and Hansell (1987). In a fuel-restricted atrium, transient fuels must not be overlooked when selecting a design fire. The minimum fire is often considered as occupying 9.29 m² of floor area. The HRR of the minimum transient fire is (225 kW/m²)(9.29 m²) = 2100 kW. The HRR of the minimum fire with combustibles is (500 kW/m²) × (9.29 m²) = 4600 kW. However, the area involved in fire can be much greater, and large fires can easily occupy 22 to 52 m² of floor area. This translates to large fires ranging from 11 000 to 26 000 kW. Table 9 lists some steady design fires, but an engineering analysis as discussed in Chapter 5 of the *Smoke Control Handbook* can result in different fire sizes.

Atrium Smoke Filling

Atrium smoke filling is only applicable to very large atriums. Atrium smoke filling time can be calculated by empirical equations for steady fires and for *t*-squared fires in NFPA *Standard 92* and Chapter 15 of the *Smoke Control Handbook*. These equations are based on the conventional approach of keeping smoke from coming into contact with occupants during evacuation. In very large atriums, smoke can often be diluted to an extent that favors the use of a tenability system (see the section on Tenability Systems).

Loss of Buoyancy in Atriums

For some applications, loss of buoyancy can cause the smoke layer to descend and threaten occupants. There is little research on this event, but the geometry of the large-volume space and the fire's heat release rate are major factors. Spaces that are unusually large or unusually long are of particular concern; for these cases, draft curtains can divide up the atrium into several smaller spaces. Theoretically, CFD modeling can predict loss of buoyancy in a large-volume space, but this has not been experimentally verified.

Table 9 Steady Design Fire Sizes for Atriums

	kW
Minimum fire for fuel-restricted atrium	2100
Minimum fire for atrium with combustibles	4600
Large fires	11 000 to 26 000

Note: These fire sizes apply to fire in the atrium space, but not to fires in communicating spaces in fully sprinklered buildings.

Minimum Smoke Layer Depth

The ceiling jet and smoke flow under the jet each have a depth of about 10% of the floor-to-ceiling height. Thus, the minimum smoke layer depth should be 20% of the floor-to-ceiling height, except when an engineering analysis using full-scale data, scale modeling, or computational fluid dynamic (CFD) modeling indicates otherwise (see the section on CFD Modeling). For information about scale modeling and full-scale fire testing, see Chapters 21 and 22 of the *Smoke Control Handbook*.

Makeup Air

Makeup air must be provided to ensure that exhaust fans can move the design air quantities and to ensure that door-opening force requirements are not exceeded. Makeup air can be provided using fans, openings to the outdoors, or both. Supply points for makeup air must be below the smoke layer interface.

The makeup air system should be designed to provide 85 to 95% of the exhaust mass flow rate. The remaining 5 to 15% of makeup air enters as leakage through cracks in the construction, including gaps around closed doors and windows. Evaluation of this leakage needs to take energy standards into account.

Hadjisophocleous and Zhou (2008) and Zhou and Hadjisophocleous (2008) show that, for makeup air velocities exceeding 1.02 m/s, the plume can be deflected, resulting in an increase in smoke production. For even higher velocities, the plume and smoke layer interface can be disrupted. The maximum air velocity must not exceed 1.02 m/s if the makeup air could come into contact with the smoke plume, unless a higher velocity is supported by engineering analysis. A secondary reason for the 1.02 m/s restriction is that it reduces the potential for fire growth and spread caused by airflow. For systems using fans, the exhaust fans should operate before the makeup air system does.

When makeup air is supplied through openings, the wind can affect makeup air velocity. When makeup air openings are on walls facing different directions, wind can increase the makeup air velocity. A simple approach is to have all makeup air openings on walls facing the same direction. When makeup air openings are on walls facing different directions, a wind analysis is suggested to mitigate the possibility of excessive makeup air velocity.

Stratification and Detection

A layer of hot air often forms under the ceiling of an atrium because of solar radiation on the atrium roof. Although no studies have been made of this stratification layer, building designers indicate that its temperature can exceed 50°C. Temperatures below this layer are controlled by the building's heating and cooling system.

When the average temperature of the plume is lower than that of the hot-air layer, a stratified smoke layer will form beneath the hot-air layer. In this situation, smoke cannot be expected to reach the atrium ceiling, and smoke detectors mounted on that ceiling cannot be expected to go into alarm.

Beam smoke detectors can overcome this detection difficulty. The following approaches can provide prompt detection regardless of air temperature under the ceiling when a fire begins:

- **Upward-Angled Beam to Detect Smoke Layer.** One or more beams are aimed upward to intersect the smoke layer regardless of the level of smoke stratification. For redundancy, more than one beam smoke detector is recommended. Advantages include not needing to locate several horizontal beams, and minimized risk of false activation by sunlight (a risk with some beam smoke detectors), because the receivers are angled downward. Review the manufacturer's recommendation when using beam smoke detectors for this application, because some beam detectors are not recommended for upward-angled installation.

- **Horizontal Beams at Various Levels to Detect Smoke Layer.** One or more beam detectors are located at roof level, with additional detectors at lower levels. Exact beam positioning depends on the specific design, but should include beams at the bottom of identified unconditioned spaces and at or near the design smoke level, with several beams at intermediate positions.
- **Horizontal Beams to Detect Smoke Plume.** Beams are arranged below the lowest expected stratification level. These beams must be close enough to each other to ensure intersection of the plume; spacing should be based on the width of the plume at the least elevation above a point of fire potential.

All components of a beam smoke detector must be accessible for maintenance, which may require maintenance openings in walls or the roof depending on the application.

Equations for Steady Smoke Exhaust

This section describes the algebraic equation method for analysis of atrium smoke control systems with a steady fire. A steady atrium smoke exhaust system has a steady smoke layer interface and a fire with a constant HRR. The smoke layer interface is the same as described in the section on Zone Fire Modeling, and the equations used here are used in some zone fire models. There is some diluted smoke below the smoke layer interface, but this assumed to not be significant. CFD modeling can calculate tenability of this diluted smoke.

For a case study of an engineering analysis for a three-story atrium that uses the algebraic equations of this section, see Chapter 16 of the *Smoke Control Handbook*. This case study addresses (1) the impact of wind, (2) determination of the minimum smoke layer depth, (3) system activation with a stratified hot-air layer, (4) analysis of design scenarios, (5) calculation of smoke exhaust for a fire in the atrium, (5) calculation of smoke exhaust for a fire with a balcony spill plume, (6) determination of makeup air, and (7) evaluation of the number of exhaust inlets and separation between them to prevent plugholing.

Readers who need to analyze atriums by the equation method may want to use AtriumCalc (Klote 2013), which uses common routines for designing atrium smoke control systems. For example, one routine calculates the smoke exhaust needed to maintain a steady smoke layer height when there is a steady design fire in the atrium with an axisymmetric plume. Each routine can be printed on a page suitable to be inserted in an engineering report. The page consists of a relevant figure, the equations used for calculation, input, and output. Other routines address balcony spill plumes, window plumes, preventing plugholing, and opposed airflow.

For an atrium fire, most of the heat flows upward in the smoke plume, and practically the rest of the heat leaves the fire by radiation. Heat transfer from fires by conduction is negligible. The convective heat release rate is expressed as

$$q_c = \chi_c q \quad (19)$$

where

- χ_c = convective fraction
- q_c = convective heat release rate, kW
- q = heat release rate, kW

The convective fraction depends on the material being burned, heat conduction through the fuel, and the radiative heat transfer of the flames, but a value of 0.7 is usually used. For fire reconstruction, the specific value of the fuel being burned must be used.

Fire in Atrium

For a fire in an atrium, the mass flow rate of the plume is usually calculated by the empirical plume equations for axisymmetric plumes. Theoretically, an axisymmetric plume has a round cross

section, but the plumes of many burning objects behave like an axisymmetric plume at some distance above the fire.

For a distance above the base of fire z equal to or greater than the **limiting elevation** z_l , the mass flow of the plume is

$$m = 0.071q_c^{1/3}z^{5/3} + 0.0018q_c \quad (20)$$

For $z < z_l$, the mass flow of the plume is

$$m = 0.032q_c^{3/5}z \quad (21)$$

where

- m = mass flow in axisymmetric plume at height z , kg/s
- q_c = convective heat release rate of fire, kW
- z = distance above base of fire, m
- z_l = limiting elevation, m

The limiting elevation is approximately the average flame height, which is

$$z_l = 0.166q_c^{2/5} \quad (22)$$

A value of z in Equation (20) or (21) can be used to calculate the mass flow in the plume for any height above the base of the fire up to the smoke layer. When z is the distance from the base of the fire to the smoke layer interface, it is called the **clear height**. For a burning solid (e.g., chair, sofa, desk), the base of the fire is some distance above the floor (Figure 25). When a flammable liquid has spilled and is burning, the base of the fire is at the floor.

Figures 27 and 28 show the smoke layer temperature and the smoke exhaust rate for fires in an atrium with an axisymmetric plume. The mass flow was calculated from the preceding equations, and the smoke layer temperature and volumetric flow were calculated by equations discussed in the following sections. As shown in Figure 27, the smoke layer temperature decreases with increasing clear height. This is a consequence of air being entrained by the plume as it rises. The plume mass flow increases with height, and plume temperature decreases with height. Figure 28 shows the smoke exhaust rate for steady exhaust atrium systems, and illustrates that the smoke exhaust rate increases with clear height.

Example 3. For a 2100 kW fire in an atrium with a clear height of 11 m, what is the mass flow of the plume? The parameters are: $q = 2100$ kW, $z = 11$ m, and $\chi_c = 0.7$.

$$q_c = \chi_c q = 2100(0.7) = 1470 \text{ kW}$$

The limiting elevation is

$$z_l = 0.166q_c^{2/5} = 0.166(1470)^{2/5} = 3.1 \text{ m}$$

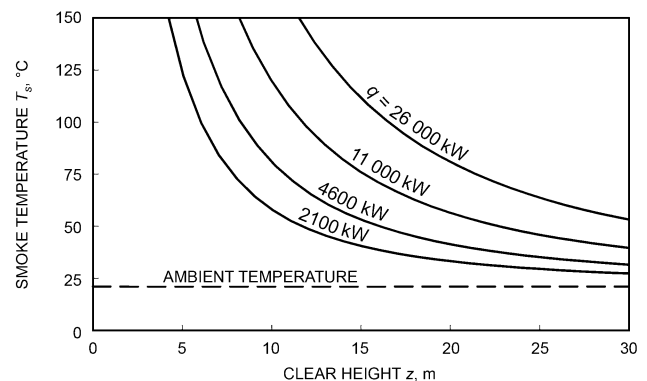


Fig. 27 Smoke Layer Temperature for Steady Smoke Exhaust Systems

Because z is greater than z_b , the mass flow of the plume is calculated with the following equation:

$$m = 0.071q_c^{1/3}z^{5/3} + 0.0018q_c = 0.071(1470)^{1/3}(11)^{5/3} + 0.0018(1470)$$

$$m = 46.6 \text{ kg/s}$$

Fire in Communicating Space

For a fire in a communicating space, usually the mass flow rate of the plume is calculated by balcony spill plume equations. The following equations are based on extensive research, including scale model fire experiments, full-scale fire experiments, and analytical studies (Ko et al. 2008; Law 1986; Loughheed and McCartney 2008a, 2008b; Loughheed et al. 2007; McCartney et al. 2008; Morgan and Marshall 1979).

The equations were developed for fire room and balcony geometry similar to that of Figure 29. If the geometry is different, CFD modeling is recommended. For z_b less than 15 m above the balcony edge, the mass flow of the plume is

$$m = 0.36(qW^2)^{1/3}(z_b + 0.25H) \quad (23)$$

Note: the mass flow equations and regions of applicability for the equations listed here have been corrected. NFPA issued errata correcting balcony spill plume equations in NFPA Standard 92-2012. There is an erratum for the bounds of one of these equations in the *Smoke Control Handbook*.

For $z_b \geq 15$ m and plume width of less than 10 m, mass flow of the plume is

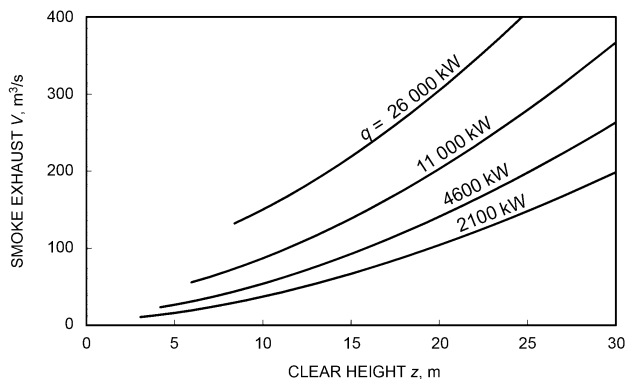


Fig. 28 Smoke Exhaust Rate for Steady Smoke Exhaust Systems

$$m = 0.59q_c^{1/3}W^{1/5}(z_b + 0.17W^{7/15}H + 10.35W^{7/15} - 15) \quad (24)$$

For $z_b \geq 15$ m and plume width between 10 and 14 m, the mass flow of the plume is

$$m = 0.2(q_cW^2)^{1/3}(z_b + 0.51H + 15.75) \quad (25)$$

where

- m = mass flow rate in plume, kg/s
- q = heat release rate, kW
- q_c = convective heat release rate of fire, kW
- W = width of the spill, m
- z_b = height of plume above balcony edge, m
- H = height of balcony above fuel, m

Physical barriers can be used to restrict the horizontal spread of smoke under the balcony. Draft curtains used for this application must extend at least 10% of the floor-to-ceiling height below the balcony. In almost all U.S. and Canadian applications, there are no draft curtains to restrict flow as shown in Figure 29. Without draft curtains, the width of the spill is estimated as

$$W = w + b \quad (26)$$

where

- W = width of spill, m
- w = width of opening from area of origin, m
- b = distance from opening to balcony edge, m

Example 4. For a 1000 kW shielded fire in a communicating space as shown in Figure 29, calculate the mass flow of the balcony spill plume. There are no draft curtains to restrict the smoke flow under the balcony. The parameters are $q = 1000$ kW, $z_b = 8$ m, $H = 3.4$ m, $b = 1.8$ m, and $w = 4$ m.

The width of the spill is

$$W = w + b = 5.8 \text{ m}$$

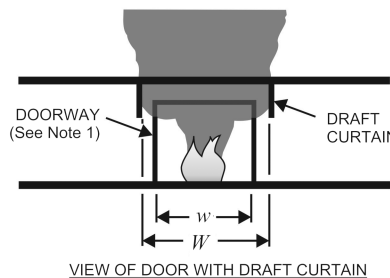
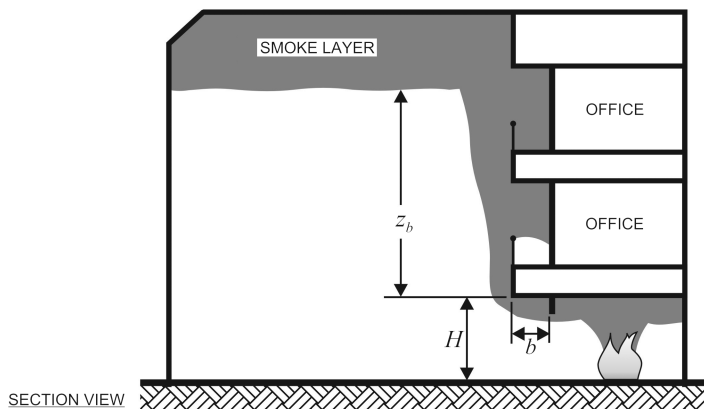
Because z_b is less than 15 m, the following equation is used to calculate the mass flow of the balcony spill plume:

$$m = 0.36(qW^2)^{1/3}(z_b + 0.25H) = 0.36[1000(5.8)^2]^{1/3} [8 + 0.25(3.4)]$$

$$m = 103 \text{ kg/s}$$

Smoke Layer Temperature

The smoke layer temperature is calculated from



- Notes:
1. Doorway height of fire room is not more than 90% of H .
 2. Atrium smoke exhaust is not shown.

Fig. 29 Balcony Spill Plume

$$T_s = T_o + \frac{Kq_c}{mC_p} \quad (27)$$

where

- T_s = smoke layer temperature, °C
- T_o = ambient temperature, °C
- K = fraction of convective heat release contained in smoke layer
- q_c = convective heat release rate, kW
- C_p = specific heat of plume gases, 1.0 kJ/(kg·K)
- m = mass flow rate of plume where it enters smoke layer, kg/s

Equation (27) applies to both axisymmetric plumes and balcony spill plumes. For atrium smoke control systems, it is believed that K varies from 0.5 to 1.0. For calculating the volumetric flow rate of smoke exhaust with Equation (23), use a value of $K = 1.0$ because it results in the highest smoke exhaust, which is conservative. For plugholing calculations, use a value of $K = 0.5$ because it results in the largest number of exhaust inlets, which is also conservative. Other values of K may be used for these applications if they are supported by test data or an engineering analysis. The mass flow rate is calculated from Equations (20) or (21), with z being the clear height.

Volumetric Flow of Smoke Exhaust

Volumetric flow of smoke exhaust is

$$V = \frac{m}{\rho} \quad (28)$$

where

- V = volumetric flow rate of smoke exhaust, m³/s
- m = mass flow rate of smoke exhaust, kg/s
- ρ = density of smoke, kg/m³

The density of smoke can be calculated from

$$\rho = \frac{p_{atm}}{RT_s} \quad (29)$$

where

- ρ = density of smoke, kg/m³
- p_{atm} = atmospheric pressure, Pa
- R = gas constant, 287 J/(kg·K)
- T_s = absolute temperature of smoke, K

The standard atmospheric pressure p_{atm} for many locations is provided in Chapter 2 of the *Smoke Control Handbook*.

Example 5. What is the volumetric flow rate for the mass flow rate from Example 3? A few minutes after system activation, the air temperature in the atrium is the same as that of the outdoors, and the largest volumetric flow rate happens during summer when it is hot outdoors. The summer outdoor design temperature is 35°C. The parameters are $T_o = 35^\circ\text{C}$, $m = 46.6$ kg/s, $q_c = 1470$ kW, $C_p = 1.0$, $R = 287$ J/(kg·K), and $p_{atm} = 101.3$ kPa. For calculation of smoke exhaust, $K = 1$.

$$T_s = T_o + \frac{Kq_c}{mC_p} = 35 + \frac{1(1470)}{46.6(1)} = 67^\circ\text{C} \quad (340 \text{ K})$$

$$\rho = \frac{p_{atm}}{RT_s} = \frac{101\,300}{287(340)} = 1.04 \text{ kg/m}^3$$

$$V = \frac{m}{\rho} = \frac{46.6}{1.04} = 44.8 \text{ m}^3/\text{s}$$

Number of Exhaust Inlets

When the flow rate of a smoke exhaust inlet is relatively large, cold air from the lower layer can be pulled into the smoke exhaust. This phenomenon is called **plugholing**. Multiple exhaust air inlets may be needed to prevent plugholing. The maximum volumetric

flow rate that can be exhausted by a single exhaust inlet without plugholing is calculated by

$$V_{max} = 4.16\gamma d^{5/2} \left(\frac{T_s - T_o}{T_o} \right)^{1/2} \quad (30)$$

where

- V_{max} = maximum volumetric flow rate without plugholing at T_s , m³/s
- T_s = absolute temperature of smoke layer, K
- T_o = absolute ambient temperature, K
- d = depth of smoke layer below lowest point of exhaust inlet, m
- γ = exhaust location factor

The ratio d/D_i should be greater than 2 where D_i is the diameter of the exhaust inlet. For exhaust inlets centered no closer than $2D_i$ from the nearest wall, $\gamma = 1$ should be used; for less than $2D_i$, $\gamma = 0.5$ should be used. For exhaust inlets on a wall, use $\gamma = 0.5$. For rectangular exhaust inlets, calculate D_i as

$$D_i = \frac{2ab}{a+b} \quad (31)$$

where

- a = length of the inlet, m
- b = width of the inlet, m

The variables a and b can be in any unit of length provided that they are both in the same units. For square inlets, D_i equals the side of the square. Where multiple inlets are needed to prevent plugholing, the minimum separation between inlets should be

$$S_{min} = 0.9V_e^{1/2} \quad (32)$$

where

- S_{min} = minimum edge-to-edge separation between inlets, m
- V_e = volumetric flow rate of one exhaust inlet, m³/s

Example 6. For the fire of Example 5, determine the number of smoke exhaust inlets and the minimum separation between them to prevent plugholing. The smoke layer is 3.2 m deep. Because the inlets in the ceiling far from walls, $\gamma = 1$. Plugholing will be calculated for an ambient temperature of 21°C. The parameters are $\gamma = 1$, $d = 3.2$ m, $T_o = 21^\circ\text{C}$ (294 K), $m = 46.6$ kg/s, $q_c = 1470$ kW, $C_p = 1.0$, and $V = 44.8$ m³/s. For calculating the number of exhaust inlets, $K = 0.5$.

$$T_s = T_o + \frac{Kq_c}{mC_p} = 21 + \frac{0.5(1470)}{46.6(1.0)} = 36.8^\circ\text{F} \quad (309.8 \text{ K})$$

$$\begin{aligned} V_{max} &= 4.16\gamma d^{5/2} \left(\frac{T_s - T_o}{T_o} \right)^{1/2} \\ &= 4.16(1)(3.2)^{5/2} \left(\frac{309.8 - 294}{294} \right)^{1/2} = 17.7 \text{ m}^3/\text{s} \end{aligned}$$

V/V_{max} is $44.8/17.7 = 2.6$. This means that at least three inlets are needed to prevent plugholing.

$$V_e = 44.8/3 = 14.93 \text{ m}^3/\text{s}$$

$$S_{min} = 0.9V_e^{1/2} = 0.9(14.93)^{1/2} = 3.48 \text{ m}$$

An inlet velocity of 7.5 m/s is chosen. The area of each inlet is $14.93/7.5 = 1.99$ m².

An inlet size of 1.3 by 1.53 m is chosen, and $D_i = 2ab/(a+b) = 2(1.3)(1.53)/(1.3+1.53) = 1.41$ m.

Then $d/D_i = 3.2/1.41 = 2.27$, which meets the stipulation that this ratio has to be greater than 2.

These calculations indicate that the edges of the inlets need to be at least 3.48 m apart from each other, and at least $2D_i$ ($2 \times 1.41 = 2.82$ m) from the nearest wall. If the edges of any inlets are closer to a wall, the

calculations should be repeated with $\gamma = 0.5$. If the inlets were in the walls, γ would be 0.5.

Zone Fire Modeling

Zone fire modeling is a simple approach to simulating smoke transport. The idea of the zone fire model came from observations in early room fire experiments that a smoke plume rises above the fire, and a smoke layer forms under the ceiling. As the fire continues, the smoke layer descends, and smoke may flow out of doorways (a doorjet).

A zone fire model considers a fire compartment to be made up of an upper smoke layer and a lower nonsmoke layer. The mass flows of the smoke plume and the doorjet are calculated from empirical equations. For the zone model idealization, temperature and concentrations of constituents are considered to be constant throughout each layer. These properties change only as a function of time.

Most zone models consider that ceilings are flat and that rooms have uniform cross-sectional areas. The height of the discontinuity between these layers (the **smoke layer interface**) is considered to be the same everywhere. In the idealized model at an infinitesimal distance above the interface, the temperature and contaminant concentrations are those of the smoke layer. At an infinitesimal distance below the interface, the temperature and contaminant concentrations are those of the lower layer. Even with these simplifications, zone fire models have proven to be very useful tools for many applications, but they must be used with care. Because different zone models use different empirical equations implemented in different ways, the predictions of different zone models vary to some extent.

Many zone models were developed in the 1980s, and often had poor numerical convergence. **CFAST** is a multiroom zone fire model that has superior numerical convergence, many features, and a graphical interface (Jones et al. 2009; Peacock et al. 2012), and has been verified with full-scale fire data. CFAST and its documentation are available from NIST at no cost. Probably for these reasons, CFAST has become the de facto standard zone fire model.

CFAST can be used to simulate atrium smoke filling, and is useful for calculating sprinkler activation time. To help new users of this model get started, Chapter 18 of the *Smoke Control Handbook* has general information about zone models plus some CFAST user information.

CFD Modeling

Atrium smoke control can be analyzed by CFD modeling. For general information about CFD modeling, see Chapter 13 of the 2013 *ASHRAE Handbook—Fundamentals*. For information about fire applications of CFD modeling, see Chapter 20 of the *Smoke Control Handbook*.

The idea of CFD is to divide the space of interest into a large number of cells and to solve the governing equations for each cell. For atrium applications, the number of cells typically ranges from 100 000 to 1 000 000 or more. Obstructions such as walls, balconies, and stairs should be taken into account, and conditions at the boundaries defined. Exhaust flow at or near the top of the atrium is specified, and makeup air conditions are also defined. This allows simulation of fluid flow in considerable detail.

Although CFD modeling has significant advantages in realistically simulating smoke flow, it is computationally intensive and requires a lot of computer memory and time; it is not uncommon for a CFD simulation to run for many hours and sometimes days. Also, it produces so many numbers that the usual ways to evaluate computer output are inappropriate. Visualization methods have been developed so people can understand CFD results.

Several general-purpose CFD models are commercially available that can be used for atrium smoke control. NIST has developed the Fire Dynamics Simulator (FDS) model (McGrattan et al. 2014a, 2014b) with visualization software called Smokeview (Forney

2008). FDS, specifically developed and verified for fire applications, can be obtained from NIST at no cost (www.fire.nist.gov/fds) and has become the de facto standard CFD model for fire applications.

13. TENABILITY SYSTEMS

The smoke control systems previously discussed are conventional systems intended either to keep smoke away from occupants or to allow only incidental smoke contact deemed to be negligible. Tenability systems are different: they are designed to allow occupants to come into contact with smoke provided that a tenable environment (i.e., one in which combustion products, including heat, are limited to a level that is not life threatening) is maintained. Analysis of a tenability system consists of a smoke transport analysis and a tenability evaluation.

Tenability Evaluation

Toxic gas, heat, and thermal radiation exposure are direct threats to life, the severity of which depends on the intensity and length of exposure. Tenability evaluation considers the effects of exposure to these threats, as well as reduced visibility.

Reduced visibility does not directly threaten life, but it is an indirect hazard. It can reduce walking speed; also, when occupants and firefighters cannot see well, they can become disoriented and cannot get away from the smoke, thus prolonging their exposure. Another concern is that a disoriented person can fall from an atrium balcony, which can be fatal.

For information about calculating the effects of exposures to combustion gases and reduced visibility, see Chapter 6 of the *Smoke Control Handbook*. There is no broad consensus, but suggested visibility criteria range from 4 to 14 m. When combustion products from most materials are diluted enough to meet such visibility criteria, the hazards to life from toxic gases, heat, and thermal radiation are also eliminated for exposures up to 20 min. This means that, for most fires, tenability can be evaluated by calculating visibility, but the hazards of other exposures must also be checked.

CFD Models. CFD models have been used extensively to analyze smoke transport for tenability systems in atriums. In addition to analysis of smoke transport, the FDS model incorporates features that help evaluate tenability. An especially useful feature is the ability of FDS to calculate visibility at user-selected points.

Large Buildings. It is not practical to use CFD to simulate smoke transport in large buildings, but CONTAM can handle this simulation in extremely large buildings. With CONTAM, the user inputs the temperatures, and zone fire models can be used to evaluate fire produced temperatures in building spaces. Chapter 19 of the *Smoke Control Handbook* discusses tenability analysis using CONTAM, including an example.

14. COMMISSIONING AND TESTING

Commissioning refers to the process of examining, comparing, testing, and documenting the installation and performance of a smoke control system to ensure that it functions according to an approved design. It demonstrates to an owner that the smoke control system installed in a project meets the project's design goals.

Special inspections are a means that an **authority having jurisdiction (AHJ)** uses to determine that a smoke control system meets the code requirements. The International Building Code (IBC) has requirements for a special inspection and describes the qualifications required for a special inspector (ICC 2012).

Commissioning Process

Commissioning begins at the start of the project and continues throughout the project. ASHRAE *Guideline* 1.5 provides methods for verifying and documenting that the performance of smoke

control systems conforms with the intent of the design. For smoke control systems, an AHJ such as a building official or fire marshal typically enforces a combination of building codes, fire codes, and local standards. The intent is to determine that the system meets the owner's project requirements (OPR), including code requirements and inspections by the AHJ throughout the delivery of the project.

For successful commissioning of a system, several different people typically are involved in the process. In addition to the building owner and AHJ, the system designer, general contractor, sub-contractors, fire protection engineering consultants, and testing and balancing technicians can be involved. At the end of testing, documentation is provided that the system is working properly according to the design.

Commissioning activities can occur at multiple stages during the construction process. Duct inspections, duct leakage testing, and barrier inspections are activities that typically occur early in the construction process when the ducts and barriers are readily visible. Component testing, including airflow measurement, can occur at a midpoint in construction where power is provided to individual devices, but central monitoring and control has not yet been provided. Sequence of operations and final performance testing typically occurs when construction is nearly complete, often just before the building is intended to obtain its permits and open to the public.

Commissioning Testing

Commonly, testing and balancing (TAB) is required before formal acceptance testing to achieve the expected performance of all the components. TAB refers to the process where the as-built performance of smoke control systems is tested in the field and compared to the required design conditions. Adjustments to the installed system, such as refining the supply airflow rates, are made to ensure that the smoke control system is functioning as intended in the approved design documentation.

System performance testing is the phase where the code-specified performance parameters appropriate to the smoke control design are measured. For example, building codes require that a minimum pressure difference exist between a pressurized stairwell and other zones in the building, and that door opening force must not exceed a specified amount. In this case, performance testing would focus on measuring the pressure difference across stairwell doors and door opening forces. Some common parameters measured during smoke control system performance testing are (1) exhaust/supply airflow quantities, (2) airflow velocities at atrium or other large open space perimeters, (3) door-opening forces, and (4) pressure differences between zones.

Caution: Smoke Bomb Tests Not Recommended. Artificial smoke from smoke bombs (also called smoke candles) or any kind of artificial smoke generator is not recommended for any performance testing, because it lacks the buoyancy of hot smoke from a real building fire. Smoke near a flaming fire has a temperature in the range of 540 to 1100°C. Heating chemical smoke to such temperatures to emulate smoke from a real fire is not recommended unless precautions are taken to protect life and property.

Special Inspector

Some building codes require special inspections and tests of smoke control systems in addition to the ordinary inspection and test requirements for buildings, structures, and parts of buildings. These special inspections and tests should verify the proper commissioning of the smoke control design in its final, installed condition. Procedures for inspection and testing should be developed by the smoke control system's special inspector, with approval of the authorities having jurisdiction. The special inspector must understand the principles of smoke control, including code requirements, and should check that the components of the system are as specified

and are installed as intended, as well as whether the smoke control system performs as intended.

Periodic Testing

After a smoke control system has been commissioned, testing must still be performed periodically over the building's life to ensure the system is in proper operating condition in the event of a fire. Periodic testing includes manual testing involving ongoing inspection and maintenance, and automatic testing to determine that integral equipment is functional and operational. Automatic testing is often performed at a higher frequency than manual testing. Continued inspection and testing identifies adjustments and repairs needed to account for unforeseen changes to the building or failure of components.

Until recently, smoke control system reliability has been somewhat compromised because periodic testing was limited to manual testing. Inspections performed years after commissioning showed that some smoke control systems were inoperable, turned off, or made ineffective by modifications to equipment or the building. Reliability of smoke control systems should be significantly improved by the use of automatic weekly self testing of system components, available from Underwriters Laboratories (UL) listed equipment with the UUKL product designation.

Dampers that are part of code-mandated passive smoke barriers are not included in the automatic weekly self testing. Typically, codes require testing these dampers every four years, except in hospitals (every six years).

15. EXTRAORDINARY INCIDENTS

Extraordinary incidents, whether caused by war, terrorism, accident, or natural disaster, can affect immediate human needs such as survival and safety, and also longer-term needs such as air, water, food, and shelter. Some buildings are designed with specific features intended to make them less susceptible to extraordinary incidents. It is recommended that actuation of systems for fire and smoke protection be of higher priority than possibly conflicting automatic strategies designed to respond to other extraordinary conditions.

Some acts of terrorism use fire, and those using bombs often lead to fires. It is well known that war, terrorist attacks, and natural disasters have the potential to disrupt utilities and interfere with firefighting, and this often allows any fires that occur to grow unchecked. For these reasons, simultaneous fire and other extraordinary incidents should be considered likely, and any features intended to mitigate extraordinary conditions should be designed accordingly. For more information, see ASHRAE's (2003) report, *Risk Management Guidance for Health, Safety and Environmental Security under Extraordinary Incidents* and [Chapter 59](#) of this volume.

16. SYMBOLS

A	= area, m ²
a	= dilution rate, air changes per minute; length of inlet, m
A_a	= free area around elevator car, m ²
A_{BO}	= flow area per stairwell between building and outdoors, m ²
A_e	= effective area, m ²
A_i	= flow area of path i , m ²
A_{lr}	= leakage area between building and lobby, m ²
A_s	= cross-sectional area of shaft, m ²
A_{SB}	= flow area between stairwell and building, m ²
A_w	= area of ventilation opening, m ²
b	= distance from opening to balcony edge, m; width of inlet, m
C	= flow coefficient; concentration of contaminant at time t
C_c	= flow coefficient for flow around car
C_0	= initial concentration of contaminant
C_p	= specific heat of plume gases, 1.0 kJ/(kg·K)
C_w	= pressure coefficient

d = depth of smoke layer below lowest point of exhaust inlet, m;
 distance from doorknob to knob side of door, m
 D_i = diameter of exhaust inlet, m
 F = total door-opening force, kg
 F_{dc} = door closer force, kg
 F_R = flow area factor
 H = floor-to-ceiling height, m; height of balcony above fuel, m
 H_j = thickness of ceiling jet, m
 H_m = height limit, m
 H_w = height of ventilation opening, m
 K = fraction of convective heat release contained in smoke layer
 m = mass flow rate, m^2/s
 p_{atm} = atmospheric pressure, Pa
 p_w = wind pressure, Pa
 q = heat release rate, kW/s
 q_c = convective heat release rate, kW/s
 R = gas constant, 287 J/(kg·K)
 S_{min} = minimum edge-to-edge separation between inlets, m
 t = time, s
 T_B = temperature in building, °C; absolute temperature in building, K
 T_F = absolute temperature of fire compartment, K
 t_g = growth time, s
 T_{in} = absolute temperature of air into fire compartment, K
 T_j = absolute temperature of ceiling jet, K
 T_O = temperature of outdoors, °C or K
 T_o = absolute ambient temperature, °C or K
 T_{out} = absolute temperature of smoke leaving fire compartment, K
 T_s = temperature of shaft or stairwell, °C or K
 T_s = absolute temperature of smoke, K
 U = elevator car velocity, m/s
 U_H = velocity at wall height H , m/s
 V = volumetric flow rate, m^3/s
 V_e = volumetric flow rate of one exhaust inlet, m^3/s
 V_{in} = volumetric flow rate of air into fire compartment, m^3/s
 V_{max} = maximum volumetric flow rate without plugholing at T_s , m^3/s
 V_{out} = volumetric flow rate of smoke out of fire compartment, m^3/s
 W = door width or width of spill, m
 w = width of opening from area of origin, m
 z = distance above neutral plane or distance above base of fire, m
 z_b = height of plume above balcony edge, m
 z_l = limiting elevation, m

Greek

γ = exhaust location factor
 Δp = pressure difference, Pa
 Δp_{FS} = pressure difference from fire compartment to surroundings, Pa
 Δp_{max} = maximum design pressure difference, Pa
 Δp_{min} = minimum design pressure difference, Pa
 Δp_{SO} = pressure difference from shaft to outdoors, Pa
 $\Delta p_{u,si}$ = upper limit pressure difference from shaft to building, Pa
 η = heat transfer factor
 ρ = density, kg/m^3
 ρ_o = outdoor air density, kg/m^3
 χ_c = convective fraction

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