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DESIGN OF SMOKE CONTROL SYSTEMS FOR ELEVATOR FIRE EVACUATION INCLUDING WIND EFFECTS

by John H. Klote

Abstract

There is a rising concern for the safety of people from fire who cannot travel building emergency exit routes in the same manner or as quickly as expected of able people. One proposed solution for providing safety for persons with mobility limitations is the concept of an emergency elevator evacuation system (EEES). This paper presents information about the design of smoke control systems to prevent smoke infiltration into an EEES. Pressure differences produced when windows break both with and without wind can be significant, and the design of a smoke control system for an EEES needs to address these pressure differences. The paper identifies that wind data specifically for the design of smoke control systems is needed. The pressure fluctuations due to opening and closing building doors during fire situations can also be significant, and the design of a smoke control system for an elevator system needs to address these pressure fluctuations. An example analysis incorporating the pressure effects of broken windows, wind, and open doors illustrates the feasibility of designing smoke control systems for EEESs.

Introduction

There is a rising concern for the safety of people from fire who cannot travel building emergency exit routes in the same manner or as quickly as expected of able persons. Klote, Levin and Groner (1995) discuss the feasibility of using elevators for fire evacuation, and introduce the concept of an emergency elevator evacuation system (EEES). An EEES includes the elevator equipment, elevator shaft (hoistway), machine room, elevator lobby, as well as, protection from heat, flame, smoke, water, overheating of elevator machine room equipment, and loss of electrical power.

This paper presents information about the design of smoke control systems to prevent smoke infiltration into an EEES with an example design analysis. The ASHRAE smoke control book (Klote and Milke 1992) presents design information for pressurized elevators. However, this paper goes beyond the smoke control book to consider broken windows and the effects of wind on smoke control system performance. A method of calculating air infiltration due to wind was presented by Shaw and Tamura (1977). Aynsley (1989) developed a method of estimating the wind pressures at ventilation inlets and outlets. However, this paper extends these concepts to include wind and broken windows specifically for EEES smoke control applications.

Pressurization air can be supplied directly into each elevator lobby or it can be supplied indirectly through a hoistway connected to the lobby as shown in figure 1. While the emphasis of this paper is on indirect pressurization, the principles presented in this paper are also applicable to direct pressurization. The direct system has the added expense of an air distribution duct and possibly a duct shaft including a corresponding loss of usable floor area.

Design Pressure Differences

It is appropriate to consider both a minumum and a maximum allowable pressure difference across the lobby doors. The phrase *maintaining acceptable pressure differences* is used to mean that the smoke control system maintains pressures that are not less than the minimum allowable pressure difference and not greater than the maximum allowable pressure difference. For smoke control of an EEES, these pressure differences are maintained across the elevator lobby doors.

In this paper, the term *lobby doors* is used to mean the doors between the elevator lobby and the building, and the term *elevator doors* is used to mean the doors between the hoistway and the elevator lobby. When the EEES smoke control system is turned on, the lobby doors are automatically closed and the elevator smoke control system is activated.

The maximum allowable pressure difference should be a value that does not result in excessive opening forces for the lobby doors. The force to open a door can be calculated by an analysis of the moments on a door including the pressure difference across the door and the force of the door-closing mechanism (Klote and Milke 1992). The Life Safety Code (NFPA 101 1994) states that the force required to open any door that is a means of egress shall not exceed 133 N (30 lb). For example, a door-closing force of 45 N (10 lbs) on a 0.91 m (36 in) wide hinged door with a pressure difference of 85 Pa (0.34 in H_2O) results in a door-opening force of 133 N (30 lb). However, for an automatic opening and closing door, the maximum allowable pressure difference depends on the capabilities of the opening mechanism and not on the human force required to open the door.

The mimimum allowable pressure difference is a value intended to prevent smoke infiltration into the EEES. NFPA 92A (1993) suggests a minimum value of 25 Pa (0.10 in H_2O) for an unsprinklered building with a ceiling height of 2.74 m (9 ft). NFPA 92A also suggests a minimum value of 12 Pa (0.05 in H_2O) for sprinklered buildings.

The minimum pressure difference applies to the fire floor, because this is where the fire puts its major stress on the smoke control system. Smoke control systems that require no information about the location of the fire floor must maintain at least the minimum pressure difference across the lobby doors on all floors.

Wind Effect

The pressure that wind exerts on a surface can be expressed as

$$P_w = K_w C_w \rho_o V^2 \qquad (1)$$

where:
P_w = wind pressure on a surface, Pa (in H_2O)
C_w = dimensionless pressure coefficient
ρ_o = outside air density, kg/ m^3 (lb/ ft^3)
V = wind velocity, m/ s (mph)
K_w = coefficient, 0.50 (6.43×10^{-3})

Generally, the pressure coefficient, C_w, is in the range of -0.8 to 0.8, with positive values for windward walls and negative values for leeward walls. The pressure coefficient depends on building geometry and local wind obstructions, and the pressure coefficient varies locally over the wall surface. Values of pressure coefficient, $\overline{C_w}$, averaged over the wall area are listed in table 1 for rectangular buildings which are free of local obstructions.

The wind far above the earth is constant with elevation and is referred to as the *gradient* wind. From the ground to the gradient wind, the wind velocity increases from zero at the ground to the speed of the gradient wind (figure 2). The flow in the boundary layer is effected by irregularities of the earth's surface and obstructions such as trees and buildings. Winds near buildings which have obstructions are non-uniform with vortices and secondary flows in various directions.

However, in the absence of obstructions, the relation between velocity and elevation is frequently expressed by the power law

$$V = V_o \left(\frac{z}{z_o} \right)^n \qquad (2)$$

where:
V = wind velocity, m/ s (fpm)
V_o = velocity at reference elevation, m/ s (fpm)
z = elevation of velocity, V, m (ft)
z_o = reference elevation, m (ft)
n = wind exponent, dimensionless

There is some variation of recommended wind exponent and boundary layer thickness (Aynsley, 1989; Houghton and Carruthers, 1976; Kolousek et al., 1984; MacDonald, 1975; Sachs, 1978), but typical values are listed in table 2 and illustrated in figure 3. There is also a logarithmic relation for velocity in the boundary layer (Simiu and Scanlan, 1986) which is more complicated and possibly more accurate than the power law. However, the power law has been used extensively, and it seems that this simple relationship is appropriate for initial studies and analyses of wind effects on smoke control systems.

Wind data is recorded by airports and the weather service at heights, z_o, of about 10 m (33 ft) above the ground. Therefore, a reference elevation of 10 m

(33 ft) will be used for the discussions and the example of this paper, unless otherwise stated. For buildings near obstructions to wind flow, specialized wind tunnel studies are needed to determine the wind pressures. Lamming (1994) provides wind data intended for smoke control design analysis for many locations in the United States and Canada.

System Concept

A smoke control system for an EEES should be designed to pressurize the EEES to prevent smoke flow into it. Pressurization air can be supplied to the hoistway, to the elevator lobbies or to both. Because hoistway pressurization systems have the advantage of less complicated ductwork, the following discussion focus on such systems. However, the general approach that follows can be adapted to lobby pressurization systems.

Pressure Fluctuations due to Open Doors

Smoke Control systems must be designed to maintain design pressure differences with both opened and closed doors. During a fire, it is expected that several exterior doors will be propped open, and stairwell doors will be opened and closed as people use the stairs. The elevator lobby doors will open and close as people enter the elevator lobby. It is envisioned that elevator lobbies will have doors with automatic closers (or have automatic doors). However, these doors can be inadvertently blocked open. It is anticipated that occupants will close any such opened doors to prevent being exposed to smoke. The example presented later presents one way of dealing with pressure fluctuations due to doors opening and closing.

Broken Windows and Wind Forces

Often, the elevated temperatures of fires result in broken windows. As indicated by Klote, Nelson, Deal and Levin (1992), fully involved room fires that have resulted in multiple fatalities also result in broken windows in the fire compartment. A smoke control system should be capable of maintaining acceptable pressure differences with a window broken for both conditions of zero wind and a design wind. Further, the wind orientation is significant in that the wind may be blowing into the window or it may be sucking out through the window.

Table 3 lists velocities and wind pressures at elevations 35 m (115 ft) and 100 m (330 ft) for velocities of 7, 9 and 11 m/s (16, 20 and 25 mph) at the reference elevation of 10 m (33 ft). The wind pressures vary from 48 to 210 Pa (0.19 to 0.84 in H_2O). These pressures are significant in comparison with the design pressure differences discussed earlier, and the example presented later will show that designing for wind effects can be challenging.

Applicability of Indirect Pressurization

For indirect pressurization systems, the pressure differences and flow areas connected to an elevator lobby are related as

$$\frac{\Delta P_{rb}}{\Delta P_{sr}} = \left(\frac{A_{sr}}{A_{rb}}\right)^2 \qquad (3)$$

where:

ΔP_{rb} = pressure difference from lobby to building space, Pa (in H_2O)
ΔP_{sr} = pressure difference from hoistway to the lobby, Pa (in H_2O)
A_{rb} = flow area between the lobby and the building space, m^2 (ft^2)
A_{sr} = flow area between the hoistway and the lobby, m^2 (ft^2)

For elevator doors with wide gaps, which are common in most buildings, Tamura and Shaw (1976) showed that the leakage area of the gaps is in the range of 0.05 to 0.07 m^2 (0.5 to 0.7 ft^2). Based on general experience with building leakages, A_{sr}/A_{rb} is about 2.5 for average construction and 10 for tight construction$_1$. From equation (3), $\Delta P_{rb}/\Delta P_{sr}$ is therefore 6.25 and 100 for average construction and tight construction, respectively. This is good for system performance, because the pressure difference of interest, from the lobby to building (ΔP_{rb}), is large relative to the pressure difference from shaft to lobby (ΔP_{sr}). To prevent smoke infiltration from the building into the lobby, the pressure difference, ΔP_{rb}, from lobby to building space should be within the range of design values previously discussed. However, if the area ratio, A_{sr}/A_{rb}, is small, direct pressurization of the elevator lobby is recommended.

Systems to Deal with Fluctuations

Smoke control systems should be able to maintain adequate pressurization under likely conditions of open doors, closed doors, broken windows and wind. Klote and Milke (1992) discuss approaches for elevator smoke control to deal with pressure fluctuations due to the opening and closing of doors. The approaches are: pressure-relief venting, barometric damper venting, variable-supply air, and fire floor exhaust. It is believed that these approaches can be adapted to include windows breaking and wind effects. This is done with a variable-supply air system in the example analysis.

Pressure-Relief Venting This approach uses a vent to the outside and a "constant-supply[2]" fan. The area of the vent is sized for operation of the smoke control system. The vent may be fitted with automatic dampers if it is desired for it to be normally closed. The vent must be large enough that the maximum pressure difference is not exceeded when all the doors are closed. When paths to the outside are open (doors and broken window), air flows through them and the pressure in the hoistway and elevator lobby drops. This system must maintain the minimum allowable pressure difference when a design number of doors and windows are open under design wind conditions.

Barometric Damper Venting This approach is similar to the one above, except that the vent has a barometric damper which closes when the pressure falls below a specified value. This minimizes air losses under the low pressure conditions.

Variable-Supply Air Variable-supply air can be achieved by using one of many fans commercially available for variable flow rate. Alternatively, a fan bypass arrangement of ducts and dampers can be used to vary the flow rate supplied to the shaft or to the lobby. The flow rate is controlled by static pressure sensors located between the lobby and the building.

Fire Floor Exhaust Exhausting smoke from the fire floor can improve the pressure difference across the lobby doors on the fire floor. Upon detection of fire, the fire floor is exhausted. The detection system must be configured to identify the fire floor.

Analysis of Smoke Control Systems

Smoke control systems can be analyzed by the computer program for analysis of smoke control systems (ASCOS) presented by Klote and Milke (1992). In this program, a building is represented by a network of spaces or nodes, each at a specific pressure and temperature. Shafts such as hoistways (elevator shafts) and stairwells are modeled by a series of vertical spaces, one for each floor.

In this model, air from the outside can be introduced by a pressurization system into any level of a shaft or even into other building spaces. This allows simulation of elevator smoke control systems. The flows and leakage paths are considered to be at the mid-height of each level. The net air supplied by the HVAC system or by the pressurization system is considered constant and independent of pressure. The outside air temperature is considered constant. The program calculates the steady flows and pressures throughout the network, including the driving forces of wind, the pressurization system, and inside-to-outside temperature difference.

Example Application

An eleven-story building with the typical floor plan shown in figure 4 was selected for this example. The height between floors is 3.0 m (10 ft). The elevator lobbies are indirectly pressurized by air injected into the second floor of the hoistway. The only smoke control system in this building is for the elevator. This analysis considers that any vent that may exist at the top of the hoistway is tightly closed during smoke control operation.

Most of the corridor doors are considered open, and so the pressure in the corridor and office space is nearly the same for a floor. In the ASCOS runs of this building, the building space on each floor is modeled as one node. The elevator lobby on each floor is another node. The minimum and maximum allowable design pressure differences are 25 and 85 Pa (0.10 and 0.34 in H_2O). The design temperatures[3] are listed in table 4.

General flow areas for this example are listed in table 5. These general flow areas were selected in an effort to be representative of those expected in the final building. Designers should arrive at such general flow areas using engineering judgement and data from various sources (such as Klote and Milke 1992, and ASHRAE 1993). However, flow areas in buildings vary over a wide range, and general values selected in this way have a high level of uncertainty. To account for this uncertainty, an approach using low and high leakage values (also in table 5) is used later in the analysis. Until noted all the flow areas are the general values.

To minimize the effect of opening and closing doors, the exterior building doors and elevator doors on the ground floor are arbitrarily chosen to be open whenever the system is operating. Elevators are often recalled to the ground floor with open doors during fires, and exterior doors are often open for evacuation and firefighter entry. Thus this condition of doors seems realistic for many applications. For buildings with other conditions of elevator or exterior doors, those conditions need to be incorporated in the analysis for that building.

For this analysis, 21 runs[4] of the ASCOS program were made with the conditions of open doors, broken windows and wind as listed in table 6. The flow of air and resulting pressure differences for the runs are listed in table 7 in SI units (table 8 in English units). These runs form a progression with conditions of later runs being based on what was learned from earlier runs. The following sections describe this progression which ends in determination of the flow rate of the supply fan and an approach for dealing with pressure fluctuations.

No Broken Windows

Runs 1 through 4 are for pressurization without a broken window and with the fire floor at the regular building temperature of 21 °C (70 °F). Any floor could be the fire floor. With all the doors closed to the elevator lobbies and the stairwells during summer (run 1), 4.48 m^3/s (9,500 cfm) of supply air is required to produce the maximum allowable pressure difference, 85 Pa (0.34 in H_2O) across the lobby door at one floor. During winter it takes 4.39 m^3/s (9,300 cfm) to produce similar pressurization (run 2).

The pressure differences in the above paragraph are considered positive when the flow is from the lobby to the building. Unless otherwise noted, pressure differences in all discussions are across the elevator lobby doors. Runs 3 and 4 are with lobby doors open on floors 2, 3 and with doors in both stairwells open on floors 1, 2, 3 and 4. The first floor stairwell door is to the outside. This group of open doors is used in these runs and several later runs to evaluate the effect of large openings from the pressurization system to the outside. Both runs were made at 4.39 m^3/s (9,300 cfm) of pressurization air which is the same as run 2. As a result of the large openings, the pressure difference dropped to the range of 30 to 32 Pa (0.12 to 0.13 in H_2O) in the summer (run 3) and 35 to 37 Pa (0.14 to 0.15 in H_2O) in the winter (run4).

For brevity, the position of the doors in runs 1 and 2 will be referred to as *closed door condition*, and the position of the doors in runs 3 and 4 will be referred to as *opened door condition*. If pressurization air were supplied at a constant rate of 4.39 m^3/s (9,300 cfm), adequate pressurization would be maintained under conditions of closed doors and opened doors, provided that no windows open. Thus, a pressure-relief vent system can maintain acceptable pressure differences when there are no broken windows. However, later runs will show that this system is not capable of dealing with the pressure variations due to broken windows under conditions of wind.

Broken Windows and No Wind

The effects of a broken window without wind on the top floor (11th story) are examined in runs 5 through 8. The top of the building was chosen for the broken window so that this would be a worst case for later runs with wind. This is a worst case with wind because wind velocity increases with elevation. For these runs and all other runs with a broken window, the temperature on the fire floor (floor 11) is 600 °C (1110 °F) as listed in table 4. However, the effect of fire floor temperature on system performance is addressed later.

In order to maintain the maximum allowable pressure difference for the closed door condition, the pressurization flow rate must be reduced by 12% during the summer (run 5) and by 33% during the winter (run 6). Breaking the window, results in a fire floor pressure that is almost the same as the outside pressure. Thus the flow rate had to be reduced to prevent excessive pressure difference across the lobby doors on that floor.

The pressure levels of the opened door condition in summer (run 7) are similar to those without a broken window (run 3). However, the open door condition in winter (run 8) results in a pressure difference of 82 Pa (0.33 in H_2O) on floor 11 as compared to 27 Pa (0.11 in H_2O) in summer (run 7). Stack effect has a tendency to increase this pressure difference in winter. The main things that runs 5 through 8 show is that a broken window can result in increased pressure difference, or the flow must be decreased to prevent excessive pressure differences.

Broken Windows, Wind and Closed Doors

Runs 9 through 12 are for the building in the closed door configuration with a broken window on floor 11, and these runs include wind effects. Runs 9 and 10 are for the broken window on the windward exposure, and runs 11 and 12 are for the broken window on the leeward exposure.

For simplicity, this building has been selected so that the leakage of the north and south walls are negligible. Thus, wind effects need to be considered for only two exterior walls (east and west). It is observed from table 5 that the leakage of the east wall is the same as that of the west wall provided that neither has a broken window. The wind coefficients for these runs were taken from table 1, and are 0.7 for the windward exposure and -0.4 for the leeward exposure. The design wind speed was 8.9 m/s (20 mph) at a reference elevation of 10 m (33 ft) in suburban terrain (n = 0.28). The same design wind velocity, wind coefficients and wind exponent are used for later runs that incorporate wind effects. It can be seen that more pressurization air is needed to maintain the same pressure difference for a windward exposure (runs 9 and 10) than for a leeward exposure (runs 11 and 12).

Broken Windows, Wind and Opened Doors

As in the above section, these runs (13-16) have included wind effects with a broken window on floor 11, but the building is in the opened door condition. The pressure differences at floor 11 are much lower when the broken window has a windward exposure (runs 13 and 14) than when it has a leeward exposure (runs 15 and 16). This is because pressure produced by wind blowing into the window reduces the pressure difference across the lobby doors. Windward exposure in the summer (run 13) is the worst case, resulting in only 2 Pa (0.01 in H_2O) across the lobby doors on floor 11 at 4.39 m^3/s (9,300 cfm) of pressurization air. This is less than the minimum allowable pressure difference, and this indicates that an approach other than pressure-relief venting is needed for this building.

For run 16, the pressure differences on most floors away from the fire are below the minimum pressure difference. As previously indicated, the minimum pressure difference only applies to the fire floor provided that the smoke control system is capable of specifically controlling the pressure difference at the fire floor. The variable-supply air system discussed above is one system that has this capability.

Variable-Supply Air

To maintain acceptable pressurization, the operation of a variable-supply air system is simulated in runs 17, 18 and 19. The system set point is selected at 25 Pa (0.10 in H_2O) across the elevator lobby door on the fire floor. The flow rate into the hoistway is controlled from a sensor on the fire floor to maintain this set point. For this example, the system is activated by a signal from a heat detector system that is zoned so that the fire floor can be identified. Other activation approaches are possible, and the reader is referred to Klote and Milke for a discussion of activation of smoke control systems. For these runs, floor 11 is considered the fire floor.

Run 17 is the same as run 2, except that the pressurization air is reduced by about 50% to maintain the above pressure difference. This flow rate [2.22 m^3/s (4,700 cfm)] is needed for the door closed condition without any broken windows.

Run 18 is the same as run 6, except the flow is again decreased in attempt to achieve the set point. Run 18 is for the closed door condition with a broken window without wind. However, a flow rate of 0.09 m^3/s (200 cfm)[5] results in 32 Pa (0.13 in H_2O) on the fire floor. This is a little greater than the set point, but this pressure difference is acceptable.

Run 19 is the same as run 13, except the flow rate was increased to 5.76 m^3/s (12,200 cfm) to maintain the set point. This run is for the open door condition with a windward exposure for the broken window. The flow rate had to be increased by about 30% to maintain an acceptable pressure difference.

Adjustment for Building Leakage

Runs 20 and 21 are the same as run 19, except that low and high leakage flow areas (table 5) were used respectively. Low and high flow areas should be based on engineering judgement and published data as the lowest and highest values that are considered acceptable construction for buildings being designed (or remodeled). However, some of the flow areas should not to be changed for the runs with low and high leakage. The areas of broken windows, opened doors, and leakage of elevator doors may be the same for all cases. The low leakage area building (run 20) requires about

14% less pressurization air than does the general leakage area building (run 19). The high leakage area building (run 21) requires about 14% more pressurization air.

Adjustment for Building Leakage and Safety Factor

A safety factor should be used to account for leakage paths not considered in the analysis and other factors that may effect system performance. The flow rate from run 21 was 6.56 m^3/s (13,900 cfm). For a safety factor of 15%, the pressurization supply fan would be sized at 7.54 m^3/s (16,000 cfm). As previously stated, over-pressurization is prevented by using the variable-supply air approach with a set point of 25 Pa (0.10 in H_2O) across the elevator lobby door on the fire floor.

Effect of Fire Floor Temperature

As previously stated, the runs with broken windows were made with a fire floor temperature of 600 °C (1110 °F). To evaluate the effect of the fire floor temperature, all of these runs were recalculated with a fire floor temperature of 21 °C (70 °F). It may be surprising that the fire floor temperature had almost no effect on the pressure differences and flows throughout the building. The reason is that the dominating effect in these runs was the pressurization system. The pressure difference calculated by ASCOS is at the mid-height of each floor, and a minimum design pressure difference of 25 Pa (0.10 in H_2O) was selected so that pressurization forces dominate the buoyancy forces of the fire gases.

The fire floor temperature also has an effect on the mass flow through the broken window. Mass flow rate in ASCOS is calculated by a form of the orifice equation

$$m = CA\sqrt{2\rho\Delta P} \qquad (4)$$

where:
m = mass flow rate, kg/s
C = flow coefficient, dimensionless
A = flow area, m^2
ρ = density of gas in flow path
ΔP = pressure difference across flow path, Pa

The units for these quantities are given only in SI units, because all internal calculations by ASCOS are in SI units. Because gas density decreases with increasing temperature, it can be seen from the above equation that the mass flow also decreases with increasing temperature. However, the flow also depends on the other paths in the building, as can be illustrated by the idea of effective flow area. When two paths in series have the same flow coefficients, the effective area of these paths is

$$A_e = T_e^{1/2}\left(\frac{T_1}{A_1^2} + \frac{T_2}{A_2^2}\right)^{-1/2} \qquad (5)$$

where:
A_e = effective flow area, m^2 (ft^2)
T_e = absolute temperature in effective path, K (°R)
T_1 = absolute temperature in flow path 1, K (°R)
T_2 = absolute temperature in flow path 2, K (°R)
A_1 = area of flow path 1, m^2 (ft^2)
A_2 = area of flow path 2, m^2 (ft^2)

The value of the temperature, T_e, in the effective path is arbitrary, and it can be selected as either T_1 or T_2. For this example, the two paths in series are the broken window (path 1) and the leakage from the lobby to the building (path 2). Using T_e = 294 K (530 °R), T_1 = 873 K (1570 °R), T_2 = 294 K (530 °R), A_1 = 1.86 m^2 (20.0 ft^2), A_2 = 0.039 m^2 (0.42 ft^2); the effective flow area, A_e is 0.038975 m^2 (0.41952 ft^2). The reason for listing this area to so many places is apparent when calculations are made with the fire floor at the normal building temperature of T_1 = 294 K (530 °R), when A_e is 0.038991 m^2 (0.41967 ft^2). The high value of the floor temperature amounted to only a 0.04% decrease in the effective flow area. Because mass flow rate is directly proportional to the effective flow area, the high fire floor temperature results in a decrease of only 0.04% in the mass flow rate. For smoke control applications, this decrease is insignificant.

In this example the broken window is so large that the fire floor pressure is almost the same as the outside pressure, regardless of the fire floor temperature. The fire floor temperature has an insignificant effect on the pressure difference and mass flow across the lobby door, provided that the pressurization system maintains at least 25 Pa (0.10 in H_2O) across the doors of the elevator lobby.

Conclusions

1. *Feasibility*: It is feasible to design smoke control

systems for elevators. The example calculation in this paper was for a specific pressurization system in a specific building, but many other systems are possible.

2. *Opening and Closing Doors*: The pressure fluctuations due to opening and closing building doors during fire situations can be significant, and the design of smoke control systems for elevators need to address the effects of opening and closing doors.

3. *Broken Windows*: The pressure differences produced when windows break both with and without wind can be significant, and the design of smoke control systems for elevators need to address these pressure differences.

4. *Indirect Pressurization*: A system that indirectly supplies air to the elevator lobby thorough the hoistway can be designed to control smoke effectively.

5. *Fire Temperature*: The fire floor temperature has no significant effect on the performance of the pressurization system for elevator evacuation system, provided that the pressurization system maintains at least 25 Pa (0.10 in H_2O) across the doors of the elevator lobby.

Notes

1. Table 4.3 by Klote and Milke (1992) lists typical leakage areas of walls and floors of commercial buildings.

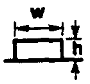
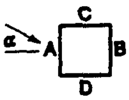
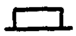
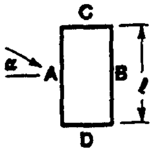
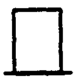
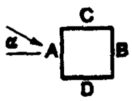
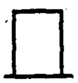
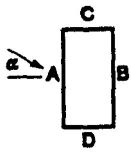
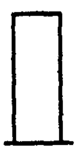
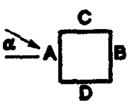
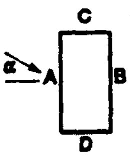
2. The supply rate is not actually constant, but varies to some extent with the pressure across the fan. For centrifugal fans this variation is usually small. The term constant-supply is used here to differentiate this approach with that of using variable-supply air flow.

3. For information about design temperatures see Klote and Milke (1992) and NFPA 92A (1988).

4. In some cases, an ASCOS run listed in table 8 is the result of executing the program a number of times to determine the flow rate that is needed to obtain a desired pressure difference at a specific location.

5. The flow rate of 0.09 m^3/s (200 cfm) was selected to represent the leakage through tight control dampers.

Table 1. Average pressure coefficients for walls of rectangular buildings (Adapted from MacDonald [1975])

Building Height Ratio	Building Plan Ratio	Elevation	Plan	Wind Angle α	$\bar{C}_w$ for Surface A	B	C	D
$\frac{h}{w} \leq \frac{1}{2}$	$1 < \frac{\ell}{w} \leq \frac{3}{2}$			0° 90°	+0.7 -0.5	-0.2 -0.5	-0.5 +0.7	-0.5 -0.2
	$\frac{3}{2} < \frac{\ell}{w} < 4$			0° 90°	+0.7 -0.5	-0.25 -0.5	-0.6 +0.7	-0.6 -0.1
$\frac{1}{2} < \frac{h}{w} \leq \frac{3}{2}$	$1 < \frac{\ell}{w} \leq \frac{3}{2}$			0° 90°	+0.7 -0.6	-0.25 -0.6	-0.6 +0.7	-0.6 -0.25
	$\frac{3}{2} < \frac{\ell}{w} < 4$			0° 90°	+0.7 -0.5	-0.3 -0.5	-0.7 +0.7	-0.7 -0.1
$\frac{3}{2} < \frac{h}{w} \leq 6$	$1 < \frac{\ell}{w} \leq \frac{3}{2}$			0° 90°	+0.8 -0.8	-0.25 -0.8	-0.8 +0.8	-0.8 -0.25
	$\frac{3}{2} < \frac{\ell}{w} < 4$			0° 90°	+0.7 -0.5	-0.4 -0.5	-0.7 +0.8	-0.7 -0.1

Note: h = height to eaves or parapit; ℓ = length (greater horizontal dimension of a building); w = width (lesser horizontal dimension of a building).

Table 2. Typical values of wind exponent and boundary layer height

Terrain	Wind Exponent n	Boundary Layer Height m	Boundary Layer Height ft
Flat (calm sea or airport)	0.16	275	900
Rough (country with trees or suburb)	0.28	400	1300
Very Rough (center of large city)	0.40	520	1700

Table 3. The effect of elevation on wind velocity and wind pressure[1]

V_o		z = 35 m (115 ft)				z = 100 m (330 ft)			
		V		P_w		V		P_w	
m/s	mph	m/s	mph	Pa	in H_2O	m/s	mph	Pa	in H_2O
7	16	10	22	48	0.19	13	29	81	0.33
9	20	13	29	81	0.33	17	38	140	0.56
11	25	16	36	120	0.48	21	47	210	0.84

[1]Wind pressure and velocity calculated from equations (1) and (2) using z_o of 10 m (33 ft), C_w of 0.8 and n of 0.28.

Table 4. Design temperatures for analysis of example smoke control system

	°C	°F
Building temperature	21	70
Fire floor temperature	600	1110
Winter outside temperature	-15	5
Summer outside temperature	32	90

Table 5. Flow areas for analysis of example smoke control system*

Location	General Values m²	General Values ft²	Low Leakage** m²	Low Leakage** ft²	High Leakage** m²	High Leakage** ft²
First floor exterior East wall (exterior doors opened)	0.975	10.5	NC	NC	NC	NC
First floor exterior West wall (exterior doors opened)	0.975	10.5	NC	NC	NC	NC
Exterior East walls above 1st floor (no broken window)	0.0204	0.220	0.0139	0.150	0.0855	0.0920
Exterior East walls above 1st floor (with broken window)	1.86	20.0	NC	NC	NC	NC
Exterior West walls above 1st floor (no broken window)	0.0204	0.220	0.00929	0.100	0.0855	0.0920
Exterior West walls above 1st floor (with broken window)	1.86	20.0	NC	NC	NC	NC
Stairwell to building (stair door closed)	0.0251	0.270	0.00929	0.100	0.0279	0.300
Stairwell to building (stair door opened)	0.975	10.5	NC	NC	NC	NC
Building floor	0.0204	0.220	0.00465	0.0500	0.121	1.30
Building to lobby (lobby doors closed)	0.0390	0.42	0.0186	0.200	0.0557	0.600
Building to lobby (lobby doors opened)	2.04	22.0	NC	NC	NC	NC
Lobby to hoistway (elevator door closed)	0.149	1.60	NC	NC	NC	NC
Lobby to hoistway (elevator door opened)	0.743	8.00	NC	NC	NC	NC

*Areas are listed to three significant figures calculations and for conversion between unit systems. However, this should not be taken an indication of accuracy, because these areas can only be roughly estimated.
**NC indicates no change from the general values.

Table 6. Arrangement of doors and wind conditions for example analysis

Run	Season	Lobby Doors Open on Floors[1]	Stairwell Doors Open on Floors[2]	Broken Window on Floors	Wind Velocity m/s	Wind Velocity mph	Wind Direction[3]	Building Leakage[4]
1	Summer	None	None	None	0	0	NA	General
2	Winter	None	None	None	0	0	NA	General
3	Summer	2,3,4	1,2,3,4	None	0	0	NA	General
4	Winter	2,3,4	1,2,3,4	None	0	0	NA	General
5	Summer	None	None	11	0	0	NA	General
6	Winter	None	None	11	0	0	NA	General
7	Summer	2,3,4	1,2,3,4	11	0	0	NA	General
8	Winter	2,3,4	1,2,3,4	11	0	0	NA	General
9	Summer	None	None	11	8.9	20	+	General
10	Winter	None	None	11	8.9	20	+	General
11	Summer	None	None	11	8.9	20	-	General
12	Winter	None	None	11	8.9	20	-	General
13	Summer	2,3,4	1,2,3,4	11	8.9	20	+	General
14	Winter	2,3,4	1,2,3,4	11	8.9	20	+	General
15	Summer	2,3,4	1,2,3,4	11	8.9	20	-	General
16	Winter	2,3,4	1,2,3,4	11	8.9	20	-	General
17	Winter	None	None	None	0	0	NA	General
18	Winter	None	None	11	0	0	NA	General
19	Summer	2,3,4	1,2,3,4	11	8.9	20	+	General
20	Summer	2,3,4	1,2,3,4	11	8.9	20	+	Low
21	Summer	2,3,4	1,2,3,4	11	8.9	20	+	High

[1]On floors where lobby doors are open, the doors on both sides of the lobby are open.
[2]1,2,3,4 indicates that, for both stairwells, the first floor exterior door and the interior doors on floors 2, 3 and 4 are open.
[3]NA indicates not applicable; + indicates that the wind is towards (or into) the broken window; - indicates the wind is away from the broken window.
[4]Flow areas for low, general and high leakage are listed in tables 3, 4 and 5.

Table 7. Computer-calculated pressure differences for smoke control example in SI units

Run	Air-flow m^3/s	Pressure difference in pascals from the elevator lobby to building on floors: 2	3	4	5	6	7	8	9	10	11
1	4.48	85	82	82	82	82	82	82	82	82	82
2	4.39	85	85	85	85	85	85	85	85	85	85
3	4.39	Open	Open	Open	32	30	30	30	30	30	30
4	4.39	Open	Open	Open	35	35	35	35	35	37	37
5	3.87	65	62	62	62	62	62	62	62	65	85
6	2.93	37	37	37	37	40	40	40	40	45	85
7	4.39	Open	Open	Open	32	30	30	30	30	30	27
8	4.39	Open	Open	Open	32	32	32	35	35	40	82
9	4.39	82	80	80	80	80	80	80	80	80	82
10	3.82	65	65	62	65	65	65	65	65	67	85
11	3.02	37	35	35	32	32	32	32	32	35	85
12	1.32	5	5	7	7	7	7	7	7	12	85
13	4.39	Open	Open	Open	32	30	30	30	27	25	2
14	4.39	Open	Open	Open	32	32	32	32	35	35	42
15	4.39	Open	Open	Open	27	27	25	25	27	30	62
16	1.51	Open	Open	Open	2	2	2	5	5	10	85
17	2.22	22	22	22	25	25	25	25	25	25	25
18	0.09	2	0	0	2	5	5	5	7	10	32
19	5.76	Open	Open	Open	55	52	50	50	50	45	25
20	4.96	Open	Open	Open	55	52	50	50	47	47	25
21	6.56	Open	Open	Open	57	55	52	52	50	47	25

Table 8. Computer-calculated pressure differences for smoke control example in I-P units

Run	Air-flow cfm	Pressure difference in inches of H_2O from the elevator lobby to building on floors: 2	3	4	5	6	7	8	9	10	11
1	9,500	0.34	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
2	9,300	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34
3	9,300	Open	Open	Open	0.13	0.12	0.12	0.12	0.12	0.12	0.12
4	9,300	Open	Open	Open	0.14	0.14	0.14	0.14	0.14	0.15	0.15
5	8,200	0.26	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.26	0.34
6	6,200	0.15	0.15	0.15	0.15	0.16	0.16	0.16	0.16	0.18	0.34
7	9,300	Open	Open	Open	0.13	0.12	0.12	0.12	0.12	0.12	0.11
8	9,300	Open	Open	Open	0.13	0.13	0.13	0.14	0.14	0.16	0.33
9	9,300	0.33	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.33
10	8,100	0.26	0.26	0.25	0.26	0.26	0.26	0.26	0.26	0.27	0.34
11	6,400	0.15	0.14	0.14	0.13	0.13	0.13	0.13	0.13	0.14	0.34
12	2,800	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.05	0.34
13	9,300	Open	Open	Open	0.13	0.12	0.12	0.12	0.11	0.10	0.01
14	9,300	Open	Open	Open	0.13	0.13	0.13	0.13	0.14	0.14	0.17
15	9,300	Open	Open	Open	0.11	0.11	0.10	0.10	0.11	0.12	0.25
16	3,200	Open	Open	Open	0.01	0.01	0.01	0.02	0.02	0.04	0.34
17	4,700	0.09	0.09	0.09	0.10	0.10	0.10	0.10	0.10	0.10	0.10
18	200	0.01	0.01	0.00	0.01	0.02	0.02	0.02	0.03	0.04	0.13
19	12,200	Open	Open	Open	0.22	0.21	0.20	0.20	0.20	0.18	0.10
20	10,500	Open	Open	Open	0.22	0.21	0.20	0.20	0.19	0.19	0.10
21	13,900	Open	Open	Open	0.23	0.22	0.21	0.21	0.20	0.19	0.10

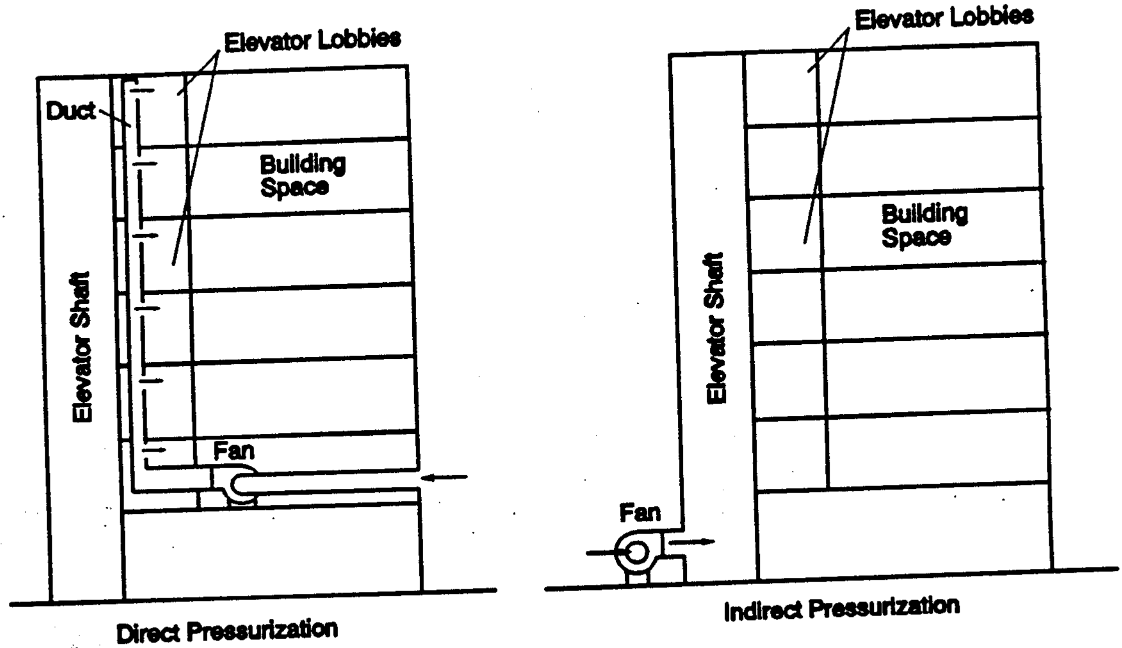


Figure 1 Direct and indirect smoke control systems for elevators

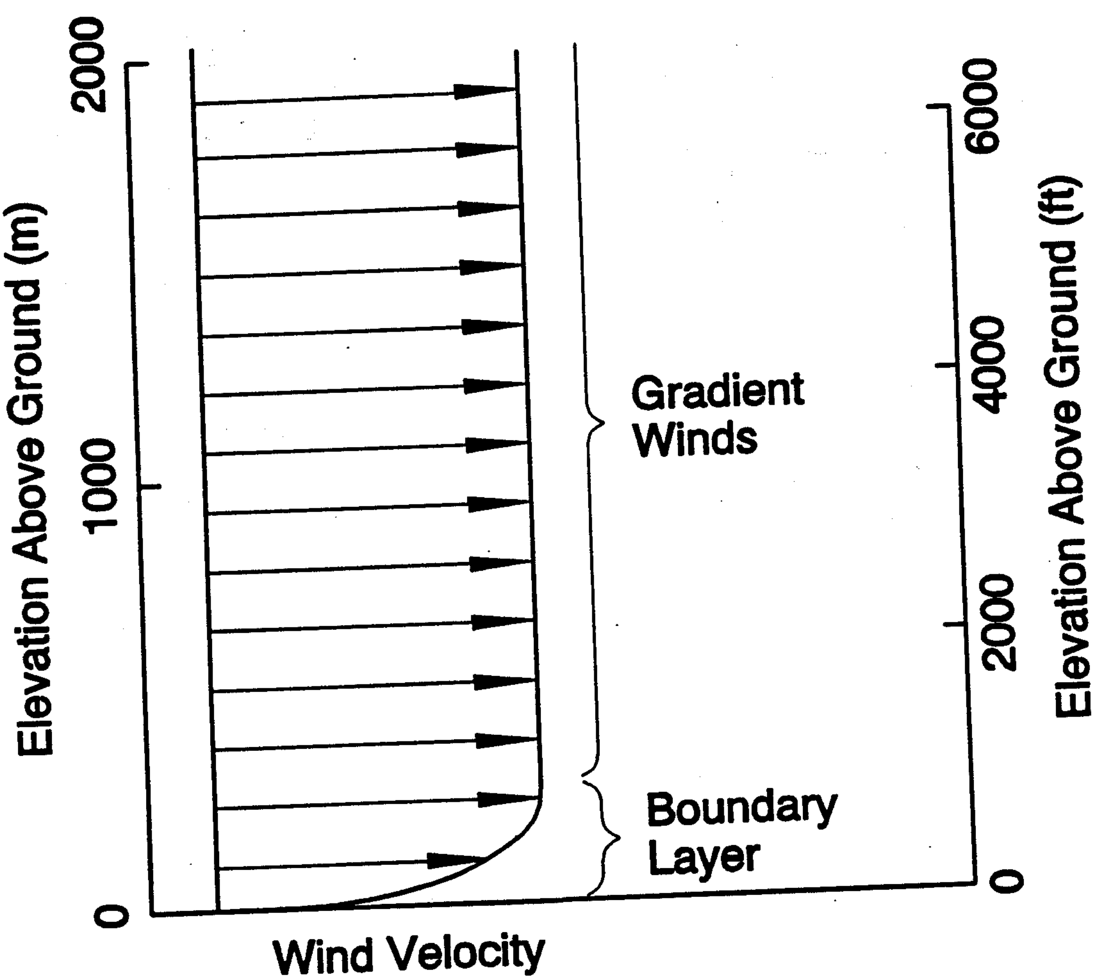


Figure 2 Gradient and boundary layer winds

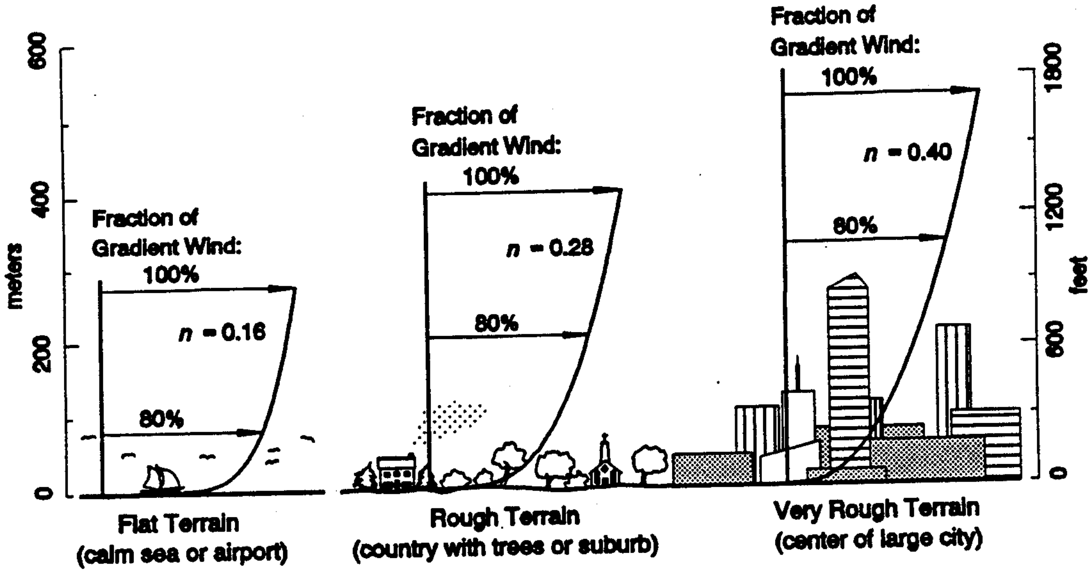


Figure 3 Wind velocity profiles for different terrain

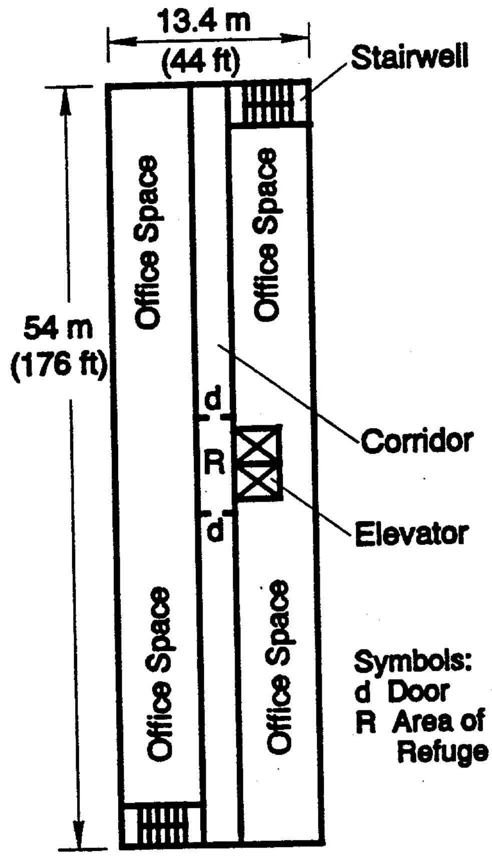


Figure 4 Typical floor plan of example building

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Dr John Klote is Head of the Building Fire Physics Group at the Center for Fire Research of the National Institute of Standards and Technology (formerly National Bureau of Standards) in Gaithersburg, Maryland. He is the primary author of the ASHRAE manual "Design of Smoke Control Systems for Buildings" and over thirty other papers on smoke control and smoke movement. Techniques used by Klote include full scale fire experiments, scale model experiments, field tests, and computer simulations. The full scale fire experiments included those at the Plaza Hotel in Washington, DC that demonstrated the effectiveness of smoke control and provided insight into the interaction of smoke control and fire growth. Dr. Klote is also active in dissemination and application of research through participation in professional soceties and standards organizations.