#3908

EXPERIMENTAL FIRE TOWER STUDIES OF ELEVATOR PRESSURIZATION SYSTEMS FOR SMOKE CONTROL

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ABSTRACT

Tests were conducted in the experimental fire tower at the National Research Council of Canada to study smoke movement through elevator shafts caused by a large fire and to determine the effectiveness of mechanical pressurization in keeping the elevator shaft and lobbies tenable for evacuation of the handicapped and for use by firefighters. The tests indicated that pressure control is required to cope with loss of pressurization due to open doors. Equations were developed to assist in designing pressure control systems involving either a variable supply air rate with feedback control or relief dampers in the walls of the elevator shaft or lobbies. Tests conducted in the tower indicated that for both methods of pressure control, comparison of measured and calculated values of supply air rates and pressure differences are in good agreement.

INTRODUCTION

It is a general practice to discourage occupants from using elevators as a means of escape during a fire by warning signs placed adjacent to the doors and by automatic elevator recall to the ground floor upon fire signals. If, however, one or more elevators can be made safe from the effects of fire, they can be used to serve a vital function in aiding firefighters and in evacuating handicapped people. Such an elevator must have controls and power supplies that are reliable, and their lobbies and shaft must be protected against fire and smoke.

To develop smoke control technology for elevators as one of the requirements of a fire-safe elevator, a joint project was undertaken by the National Research Council of Canada (NRCC) and the National Bureau of Standards (NBS) in the United States. Initial studies involved a computer analysis of several possible smoke control systems (Klote and Tamura 1986). The results of the analysis conducted for both summer and winter and for certain open-door conditions indicated that all systems considered, except for the one with feedback control of supply air for elevator shaft pressurization, failed to maintain the required pressurization when some combination of doors was open. It was also noted that there are probably other systems capable of providing adequate smoke control.

This paper deals with the follow-up studies in the experimental fire tower of the National Fire Laboratories (NRCC). The tests involved examining the smoke movement pattern caused by the temperature effect of fire and the effectiveness of the mechanical pressurization either of the elevator shaft or elevator lobbies in the elevator shaft/lobby usable. Equations were developed for designing pressurization systems with pressure control to cope with pressure loss due to some open door configurations. The types of pressure control system examined were feedback control of supply air rate for pressurization and relief dampers in the walls of either the elevator shaft or elevator lobby in the case of lobby pressurization. These equations were validated with tests in the experimental fire tower. They will probably be useful to designers; this paper, however, does not develop a complete design methodology for elevator smoke control.

DESCRIPTION OF THE EXPERIMENTAL FIRE TOWER

The fire tower (Figure 1) is part of the experimental facilities of the National Fire Laboratory located between Carleton Place and Almonte, Ontario, about 40 miles (60 km) west of Ottawa. The 10-story tower comprises an experimental tower and an attached observation tower. The typical floor height is 8.5 ft (2.6 m) except for the first and second floors, which are 12 ft (3.6 m). Both towers are constructed of monolithic reinforced concrete (thickness of 8 in [200 mm]). The plan view of a typical floor is shown in Figure 2.

The observation tower contains a freight elevator, stairway, a workspace for instruments, and data acquisition units for monitoring fire experiments. It is protected by a fire wall and fire doors with small fixed wired-glass observation windows. An independent air system maintains a comfortable temperature in winter and pressurizes the observation tower to prevent ingress of combustion products from the fire tower.

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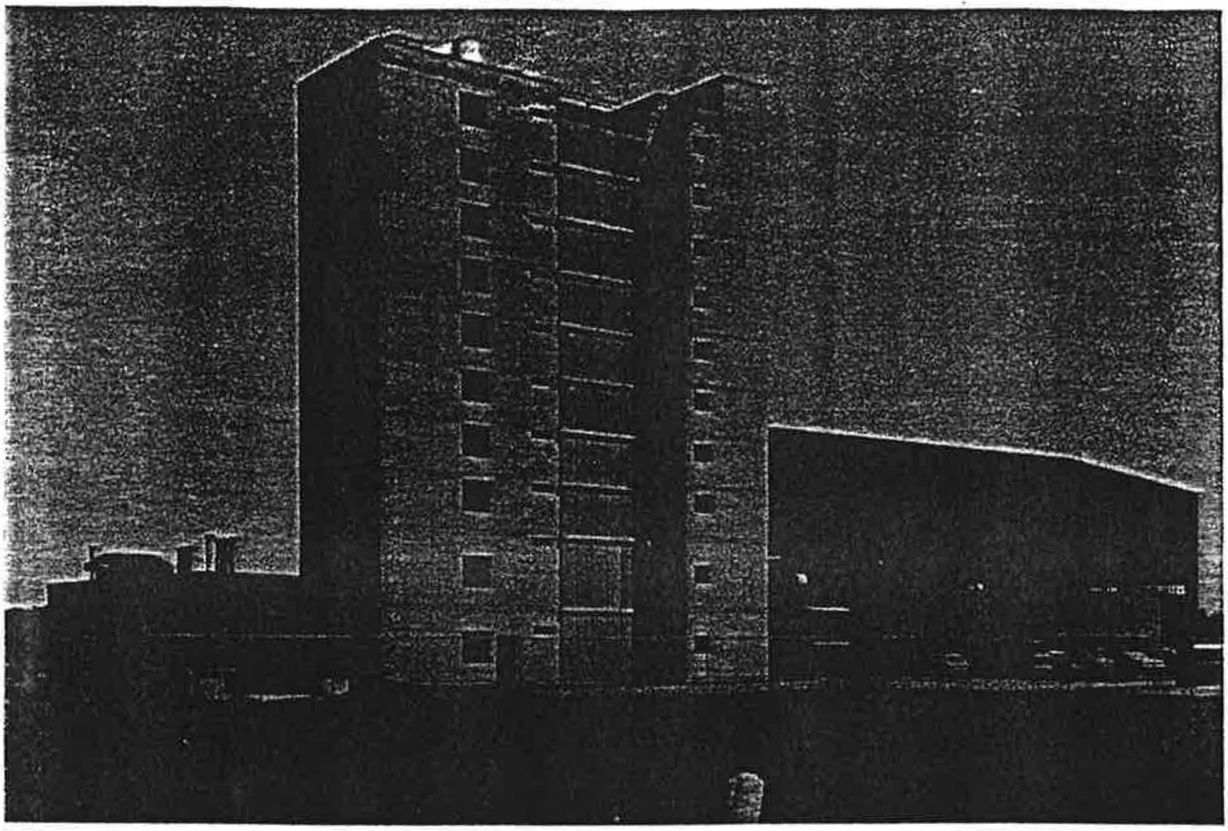


Figure 1 *Experimental fire tower*

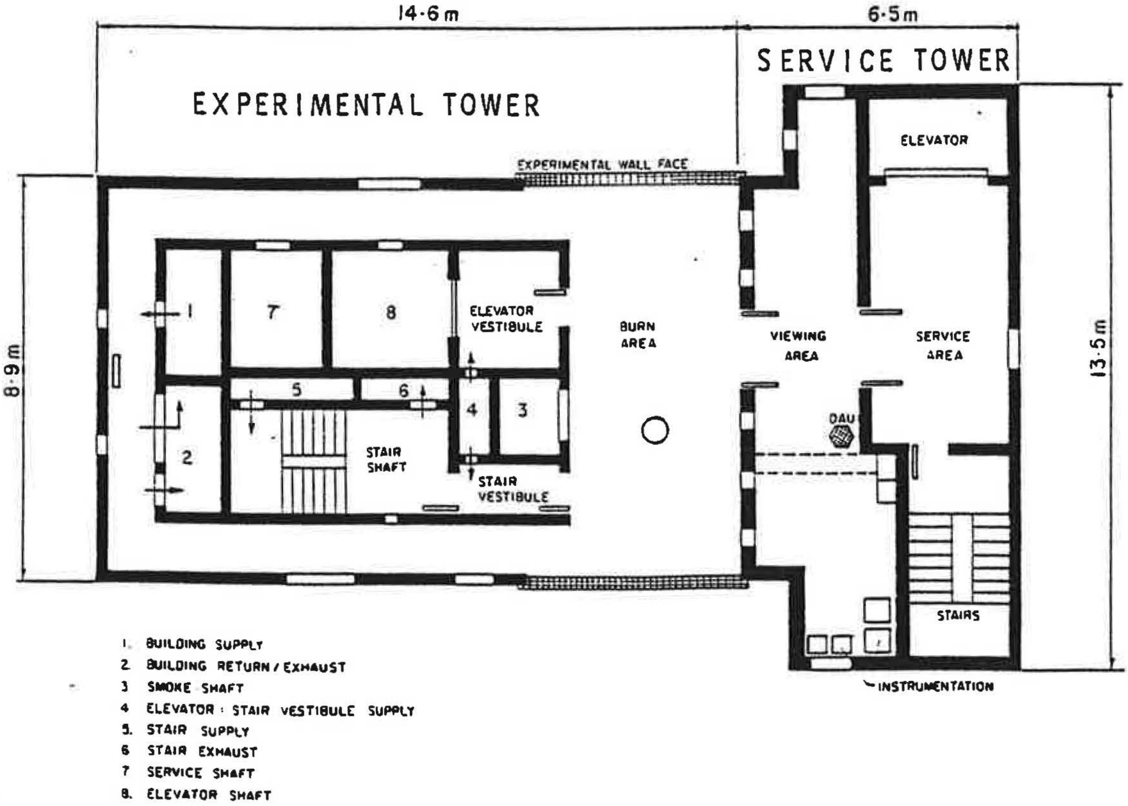


Figure 2 *Plan of the experimental fire tower*

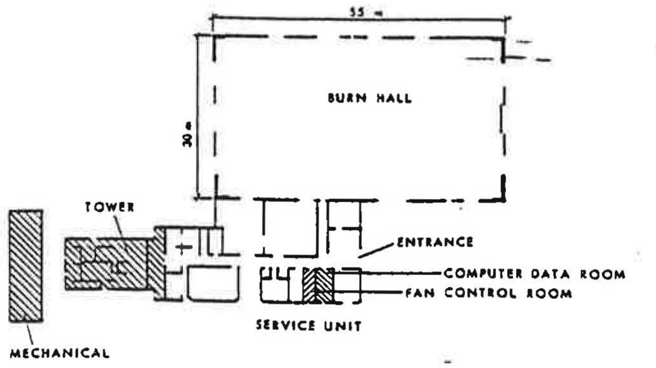
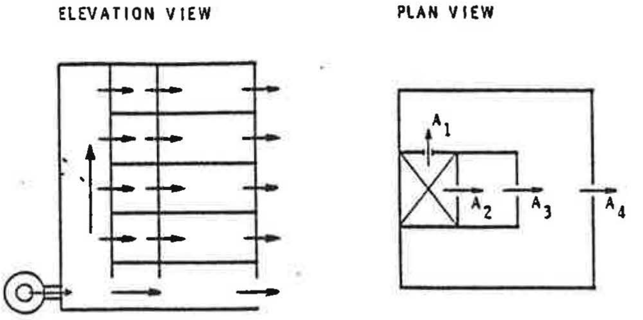
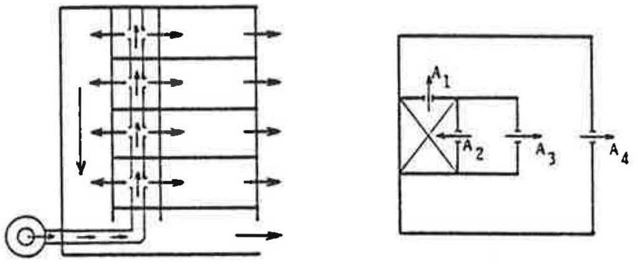


Figure 3 *Layout of the national fire laboratory*



a) PRESSURIZED ELEVATOR SHAFT



b) PRESSURIZED LOBBIES

Figure 4 *Elevator pressurization system*

The experimental tower contains all the shafts and other features necessary to simulate air and smoke movement patterns of a typical multistory building, including the elevator, stair, smoke exhaust, service, supply, and return air shafts. The elevator and stair shafts are full-sized, but the elevator shaft, at present, has no car or hoisting apparatus, while the stairshaft is equipped with a standard staircase. A surrounding corridor isolates the group of shafts from the exterior walls, creating a typical center core. All joints of the concrete structure are sealed to minimize uncontrolled air leakages. The exterior walls and walls of vertical shafts are provided with variable openings that can be set to provide desired leakage areas of typical buildings. Two propane gas burner sets, each capable of producing heat at an output of 8.56×10^6 Btu/h (2.5 MW), are located on the second floor burn area with the gas train rigs located immediately below on the ground floor. The second floor is completely protected with high-temperature insulation to prevent the concrete from thermal damage of the concrete.

A separate structure adjacent to the tower (Figure 3) houses the air moving and heating plant of the experimental tower; the air ducts being carried underground through a short tunnel to the bottom of the experimental fire tower. There are two air systems. The first handles the main air supply and heating load. It normally operates in the recirculation mode, but it can be operated on 100% outside air and used to pressurize the entire building. This system can also be run in an exhaust mode by using a separate variable-flow exhaust fan mounted at the top of the return air shaft. The second air system supplies outside air, either to the experimental stair and elevator shafts or to vestibules interposed between the entrances to these shafts and the burn area. The air systems are operated from the fan control room in the attached service unit (Figure 3). The airflow rates in the air ducts are measured with either multipoint self-averaging total pressure tubes and their associated static pressure taps or with an orifice plate. They were calibrated using the pitot traverse method.

Temperatures are measured in 10 different locations on each floor using chrome-alumel thermocouples. Additional temperature measurements are made in the burn area of the fire floor. Pressure differences across the various walls are measured using 18 static pressure taps (0.25 in [6.3 mm] O.D. copper tubing) mounted flush to the walls on each floor. All pressure lines are connected to a 24-port pressure switch equipped with a diaphragm-type magnetic reluctance pressure transducer and located on the same floor in the observation area. Carbon dioxide concentrations are measured at six locations on each floor in the shafts, lobbies, corridors, and burn area by copper sampling tubes (0.25 in [6.3 mm] O.D. copper tubing) connected to a 12-port sampling switch unit with a nondispersive infrared gas analyzer. All devices of the three systems are controlled and monitored by a computer-based data acquisition and control system.

The cross-sectional area of the elevator shaft, which represents a single car shaft, is 84 ft² (7.84 m²). Openings in the walls for the elevator doors are covered with a movable plywood panel to permit a variable-size opening up to 6.0 ft² (0.56 m²) to simulate a leakage area due to an open elevator door with the car at the opening. There is a removable hatch at the top of the elevator shaft and an outside vent connected to the bottom of the shaft at the subgrade level to permit natural venting either at the top or bottom of the shaft. Also at the subgrade level there is an opening for air supply to the shaft. The elevator lobby, whose area is 70 ft² (6.44 m²), is provided with a standard fire door on all floors except for the second floor, where the door is of plasterboard with a vertical leakage slot in the center to represent the leakage area of a typical door. There is an opening in the wall of each lobby to supply air for lobby pressurization. A more detailed description of the experimental fire tower may be found in Achakji (1987).

DESIGN APPROACH

The intent of an elevator pressurization system is to prevent smoke migration into elevator shafts and lobbies during a fire. This is done by developing pressures in the lobbies that are sufficient to overcome the adverse pressure differences caused by various mechanisms, such as weather, temperature effect of fire, ventilation systems, and the piston effect caused by an elevator in motion. Lobbies serve as temporary refuge areas for the handicapped waiting to be evacuated by an elevator; they also protect the elevator door and its control mechanism from the fire temperature. The highest adverse pressure difference for a given building due to a combination of these various mechanisms is the design pressure difference that an elevator shaft pressurization system must be capable of maintaining across the lobby door during a fire. The determination of the design pressure difference is beyond the scope of this paper and is the subject of another investigation. This paper deals only with the component of the design pressure difference caused by the temperature effect of fire.

A calculation procedure was developed to assist in designing pressure control systems involving either variable supply air or relief dampers in the walls of the elevator shaft or lobbies. Figure 4 shows the schematic drawings of both the elevator shaft and the elevator lobby pressurization systems. The leakage areas in the walls of the airflow systems are indicated in these figures. By considering equations for parallel and series flow combinations described in Klote and Fothergill (1983), the required supply air rates for a given design pressure difference, the resultant pressure differences when doors are opened, and the required relief damper sizes can be calculated. These equations for both the elevator shaft and lobby pressurization systems are listed in Appendix A. The basic equation is

$$Q = CA_e(\Delta P)^{1/2} \tag{1}$$

where

Q = supply air rate

C = constant for a standard air condition

A_e = overall equivalent leakage area from the pressurized space to outside per floor

ΔP = pressure difference from the pressurized space to outside

The values of A_e for the elevator shaft and the elevator lobby can be calculated from equations in Appendix A, step 1. For a given design pressure difference across the elevator lobby door (ΔP_3), the required ΔP can be calculated from equations in Appendix A, step 2, which show that $\Delta P_3/P$ is constant for a given set of leakage areas. The required supply air rates can be calculated from equations in Appendix A, step 3. For the open-door configuration with the elevator, elevator lobby, and exit doors on the ground floor open so that the elevator shaft is directly exposed to outside pressure, the flow rate on the ground floor from the elevator shaft to outside can be calculated with equations in Appendix A, step 4. The total outside supply air rates required to pressurize the elevator lobby to a specified design level (ΔP_3) can be calculated using equations in Appendix A, steps 5 and 7, for the case with all doors closed, Q_T, and with the ground floor doors open, Q_T', respectively. The calculation of Q_T' can include open lobby doors on other floors to conform to a given design criteria by using a suitable value of A_e on those floors, as indicated in the note in step 1. For a variable supply air fan system with feedback control, the range of supply air rate required is then given by Q_T and Q_T'.

With supply air, Q_T, set for the all-doors-closed situation, the lowered value of $\Delta P_3'$ caused by opening doors on the ground floor is given by equations in Appendix A, step 6 and, correspondingly, with supply air, Q_T' set for the open-door condition, the increased value of ΔP_3 caused by closing all doors is given by equations in step 8. The values of $\Delta P_3'$ and ΔP_3 should be checked, for in the former case, $\Delta P_3'$ may be too low to prevent smoke infiltration, whereas for the latter case, ΔP_3 may be great enough to cause difficulty in opening lobby doors. The problem of overpressurization can be overcome by providing relief dampers in the walls of either the shaft or lobby on each floor. The equation for the required size of relief damper is given in Appendix A, step 9, and the corresponding required supply air rate in step 10. A factor, L, to account for the specified increase in ΔP_3 is incorporated in the equation in step 9 for sizing the damper so that the rise in ΔP_3 when the elevator door is closed is limited to prevent difficulty in door operation. The relief dampers are closed when the elevator and lobby doors are open and they are fully open when all doors are closed.

When an elevator shaft is pressurized to achieve the required pressure difference across a lobby door on the fire floor and an elevator or lobby door on some other floor opens, the amount of pressurization is decreased due to the increase in the total leakage area of the shaft. Assuming the total quantity of pressurization air supplied to the smoke control system is constant, the relationship between the pressure difference and the leakage area before and after the door is opened can be expressed as

$$\left(\frac{\Delta P_2}{\Delta P_1}\right)^{1/2} = \left(\frac{A_1}{A_2}\right) = K \tag{2}$$

where

A = total leakage area of the shaft

Subscripts

1 = before the elevator door is open

2 = after the elevator door is open

The value of ΔP_2 should be equal to the design pressure difference to prevent smoke infiltration into the elevator shaft. The leakage areas, A_1 and A_2, can be defined as

$$A_1 = NA_e \text{ (all doors closed)} \tag{3}$$

and as an example of an open door situation

$$A_2 = (N - 1)A_e + A_o \text{ (elevator, lobby, and exit doors on the ground floor open)} \tag{4}$$

where

N = number of floors

A_e = effective leakage area from elevator shaft to outside per floor

A_o = leakage area of an open elevator door

Combining Equations 2, 3, and 4 gives

$$\left(\frac{\Delta P_2}{\Delta P_1}\right)^{1/2} = K = \frac{NA_e}{(N-1)A_e + A_o} \qquad (5)$$

For a selected value of $\Delta P_2/\Delta P_1$, ΔP_2 is above a minimum acceptable value when the elevator door is opened if

$$\frac{N}{K} - (N-1) \geqslant \frac{A_o}{A_e} \qquad (6)$$

For example, if $\Delta P_2/\Delta P_1 \geqslant 1/3$ and the minimum acceptable value of $P = 0.05$ in of water (12.5 Pa), $A_e = 0.318$ ft² (0.0295 m²), and $A_o = 6.00$ ft² (0.557 m²), then ΔP_2 is above the minimum acceptable value for a tower higher than 24 stories. This is also the case for the 10-story tower, if the value of A_o is less than 2.65 ft² (0.246 m²). The leakage area, A_o, can be decreased by tightening up the car enclosure and decreasing the clearance between the car and the door side of the shaft. For these cases, no special provision is required for pressure control to account for an open elevator door. Equation 6 is, hence, useful in the design of an elevator pressurization system to check whether pressure control is needed. If some lobby doors are assumed to be open, then the average value of A_e for the tower should be used in Equation 6.

The results of the example calculation for the tower following the procedure in Appendix A are given in Appendix B.

TABLE 1
Leakage Flow Areas per Floor of the Experimental Fire Tower

Location	Area	
Outside walls	**ft²**	**m²**
1st floor east wall	0.59	0.055
1st floor west wall	0.59	0.055
2nd floor east wall (wall vent closed)	0.59	0.055
2nd floor east wall (wall vent open)	5.00	0.464
2nd floor west wall (wall vent closed)	0.59	0.055
2nd floor west wall (wall vent open)	5.00	0.464
Typical floor east wall	0.39	0.037
Typical floor west wall	0.39	0.037
Elevator		
Floor space to elevator shaft	0.07	0.006
Floor space to elevator lobby (lobby door closed)	0.30	0.028
Floor space to elevator lobby (lobby door open)	21.00	1.951
Elevator lobby to elevator shaft (elevator doors closed)	0.75	0.070
Elevator lobby to elevator shaft (elevator doors open)	6.00	0.557
Stairs		
Floor space to stairshaft	0.04	0.004
Floor space to stair lobby (lobby door closed)	0.25	0.023
Floor space to stair lobby (lobby door open)	21.00	1.951
Stair lobby to stairshaft (stair door closed)	0.25	0.023
Stair lobby to stairshaft (stair door open)	21.00	1.951
Vertical Shafts		
Floor space to service shaft	1.10	0.102
Floor space to supply air shaft*	2.00	0.186
Floor space to return air shaft*	2.00	0.186
Ceiling	0.56	0.052

*Supply and return air openings sealed on the second floor

TEST PROCEDURE

The leakage areas of the tower were set to simulate those of a building with average airtightness and a floor area of 9730 ft² (904 m²) or seven times that of the floor area of the experimental tower. The values of leakage areas for the tower given in Table 1 were estimated from measurements of other buildings conducted by Tamura and Shaw (1976, 1978).

The initial series of tests were conducted with low and high fire temperature conditions, both following approximately the ASTM-E119 standard time-temperature curve up to the maximum test temperatures and held constant thereafter. For the low-temperature fire, intended to represent a sprinklered fire, the maximum temperature was set at 840°F (400°C). This temperature, which is probably much higher than expected in a sprinklered fire, was dictated by the minimum temperature at which the test gas burners could be operated. For the high-temperature fire, the maximum fire temperature was set at 1380°F (750°C); five minutes after ignition, the east and west wall vents on the second floor, each with an area of 5 ft² (0.46 m²), were opened to simulate broken windows. It is realized that a much higher temperature can occur in an actual fire, but the selected temperature level was considered to be adequate for the purpose of the tests. The control temperature for the burners was measured 1.0 ft (0.3 m) below the ceiling directly above the gas burners. The heat outputs were 0.92 and 2.8 × 106 Btu/h (0.27 and 0.82 MW) for the low- and high-temperature fires, respectively; the corresponding outside combustion air supplies were 385 cfm (0.18 m³/s) and 740 cfm (0.35 m³/s). The test schedule was set to monitor smoke migration during the burn periods and the performance of both the elevator shaft and lobby pressurization systems with the elevator door closed and open. The supply air for pressurization was injected at the bottom of the elevator shaft or the bottom of the air distribution shaft for lobby pressurization. For the low- and high-temperature fire tests, the elevator lobbies were pressurized to 0.05 in of water (12.5 Pa) and 0.10 in of water (37.5 Pa), respectively. For these tests, two extra pressure taps were placed 1.33 ft (0.40 m) and 6.33 ft (1.93 m) above the second floor level in the insulated plasterboard lobby door and connected to a pressure transducer whose output was recorded on a continuous pen recorder. They complemented the existing pressure tap located 10.12 ft (3.08 m) above floor level. An extra gas sampling tube was placed inside the second floor lobby and connected to an infrared gas analyzer, whose output was also recorded on a continuous pen recorder.

The fire tests were conducted on both an elevator shaft pressurization system and an elevator lobby pressurization system. Both systems were tested against low- and high-temperature fires. The pressurization system was activated for 15 minutes, shut down, and then reactivated 40 minutes after ignition of the fire to determine the pressure differences across the lobby door due to pressurization alone, fire alone, and both acting together. The low-temperature fire test with the lobby pressurization system was conducted with the pressurization system activated prior to igniting the burners to more closely simulate expected fire situations. At about 70 minutes after ignition, the first floor elevator door, lobby door, and an exterior door were

TABLE 2

CO_2 Concentrations with High-Temperature Fire —Elevator Shaft Pressurization

Unbracketed numbers—45 min. after ignition and without pressurization
Bracketed numbers—15 min. after pressurization system is activated

CO_2 concentration, % of concentration in the fire region

Floor	Burn area	Elevator lobby	Elevator shaft	Stair lobby	Stair shaft	Service shaft
10	33 (32)	- (-)	21 (0)	30 (24)	17 (28)	
9	31 (27)	19 (7)	20 (0)	28 (28)	16 (26)	33 (35)
8	31 (27)	16 (5)	21 (0)	28 (29)	15 (27)	
7	28 (26)	14 (3)	21 (0)	23 (23)	13 (27)	34 (36)
6	22 (23)	16 (2)	23 (0)	12 (13)	- (-)	
5	15 (17)	15 (2)	22 (0)	2 (8)	3 (19)	34 (36)
4	24 (26)	22 (3)	29 (0)	6 (15)	10 (27)	
3	39 (38)	19 (1)	23 (0)	4 (10)	6 (18)	33 (34)
2	100 (100)	70 (14)	35 (0)	61 (67)	18 (30)	
1	3 (3)	0 (0)	2 (0)	1 (3)	4 (13)	10 (13)

TABLE 3

CO_2 Concentrations with High-Temperature Fire —Elevator Lobby Pressurization

Unbracketed numbers—30 min. after ignition and without pressurization
Bracketed numbers—15 min. after pressurization system is activated

CO_2 concentration, % of concentration in the fire region

Floor	Burn area	Elevator lobby	Elevator shaft	Stair lobby	Stair shaft	Service shaft
10	25 (27)	- (-)	12 (3)	17 (18)	9 (19)	
9	24 (25)	10 (0)	11 (3)	13 (19)	10 (18)	30 (32)
8	23 (23)	11 (0)	11 (3)	10 (19)	8 (19)	
7	22 (24)	11 (0)	11 (3)	10 (15)	7 (18)	31 (32)
6	--	--	--	--	- (-)	
5	8 (14)	9 (0)	8 (3)	0 (19)	4 (16)	30 (32)
4	17 (22)	8 (0)	10 (5)	0 (10)	3 (19)	
3	37 (36)	5 (0)	6 (2)	1 (4)	1 (6)	28 (32)
2	100 (100)	65 (0)	22 (2)	33 (40)	9 (5)	
1	2 (4)	2 (0)	2 (5)	0 (1)	1 (3)	7 (14)

opened to study the effect of the resulting drop in pressurization.

A series of non-fire tests were conducted to verify the calculation procedures given in Appendix A. The methods of pressure control tested were for a variable supply air system and the use of relief dampers in the walls of the elevator shaft on each floor. With the elevator door closed and open, the pressure differences across the elevator lobby wall was controlled to a minimum of 0.05 in of water (12.5 Pa) to prevent smoke infiltration due to a low-temperature fire and a maximum of 0.15 in of water (37.5 Pa), which is well below the allowable limit of 0.36 in of water (90 Pa) for door operation. This latter limit was based on the requirement of the National Fire Protection Association Fire Safety Code (NFPA 1985) on the maximum allowable door opening force of 30 lb (133 N) and assuming a door size of 7 ft (2.13 m) by 3.33 ft (1.02 m) and a force of 11 lb (40 N) to overcome the door closure.

The tests were conducted with temperature differences between the inside and outside of less than 10°F (6°C) and a wind speed of less than 10 mph (16 km/h). Tests under non-fire conditions to validate the equations in Appendix A were conducted with the outside wall leakage areas for the first and second floors having the same values as those of the remaining floors to simplify validation.

RESULTS AND DISCUSSION

Smoke Migration

A detailed hazard analysis considering the effect of heat flux, toxic gases, and smoke obscuration is beyond the scope of this paper. However, a simplified approach to the smoke obscuration problem is taken assuming that particulate concentrations from a solid fuel fire would be proportional to the measured CO_2 concentrations from

TABLE 4

Temperature Rise in the Tower 30 Minutes After Ignition During a High-Temperature Fire Test

Outside temperature 45° F (7° C)

Floor	Burn area ° F (° C)	Elevator lobby ° F (° C)	Elevator shaft ° F (° C)	Stair lobby ° F (° C)	Stair shaft ° F (° C)	Service shaft
10	16 (9.3)	1 (0.8)	8 (4.7)	1 (0.4)	17 (9.2)	
9	17 (9.5)	2 (1.0)	10 (5.4)	1 (0.3)		84 (46.4)
8	17 (9.6)	2 (0.9)	11 (5.9)	1 (0.3)	22(12.3)	
7	17 (9.4)	2 (1.2)	15 (8.1)	0 (0.2)		99 (55.2)
6	14 (7.8)	2 (1.4)	16 (9.1)	0 (0)	21 (11.7)	
5	1 (0.7)	2 (1.4)	20 (11.2)	0 (0.1)		116 (64.5)
4	7 (3.7)	5 (2.7)	23 (12.6)	0 (0.2)	23 (12.8)	
3	66 (36.6)	6 (3.5)	26 (14.3)	1 (0.6)		96 (53.1)
2	1350 (750)	38 (21.2)	22 (12.4)	10 (5.4)	7 (4.1)	
1	4 (2.3)	4 (2.5)	7 (3.7)	0 (0)		0 (0.2)

TABLE 5

Pressure Differences in the Tower 30 Minutes After Ignition During a High-Temperature Fire Test

Pressure difference—in of water (Pa)
Reference pressure—burn area

Floor	Elevator lobby	Stair lobby	Return Air shaft	Service shaft
10	−0 (−0.8)	−0.01 (−2.0)	0 (0.6)	0.07 (18.7)
9	−0 (−0.7)	−0.01 (−1.9)	0 (0.5)	0.06 (14.7)
8	−0 (−0.3)	−0 (−1.1)	0 (0.6)	0.04 (10.4)
7	0 (0.0)	−0 (−0.7)	0 (0.4)	0.03 (8.0)
6	0 (0.06)	−0 (−0.1)	0.02 (5.1)	
5	0 (0.0)	0 (0.0)	--	0 (0.0)
4	0 (0.2)	0 (0.8)	−0 (−0.2)	−0.02 (−4.0)
3	0 (0.0)	0 (0.3)	−0 (−0.3)	−0.04 (−10.2)
2	−0.03 (−7.6)	−0.05 (−13.6)	−0.08 (−19.3)	−0.12 (−31.7)
1	0 (0.1)	0 (1.0)	0 (0.2)	−0.07 (−16.5)

these tests. This assumption is probably conservative in that smoke deposition reduces particulate concentration.

The CO_2 concentrations in the tower for the high-temperature fire tests 45 minutes after ignition and 15 minutes after elevator shaft pressurization at 0.10 in of water (25 Pa) are given in Table 2 and similarly after lobby pressurization in Table 3. The CO_2 concentrations are expressed as a percentage of the concentration in the second floor measured 1 ft (0.3 m) below the ceiling in the burn area. From a consideration of smoke obscuration, it can be assumed that an area is reasonably safe if it is not contaminated to an extent greater than 1% of that in the vicinity of a fire area (McGuire *et al.* 1970). It is seen that without mechanical pressurization, the CO_2 concentrations are well above the 1% level in almost all spaces including the elevator shaft and lobbies. The highest concentration, 70%, occurred in the second floor elevator lobby. The highest CO_2 concentrations in the vertical shafts occurred in the service shaft. Examination of the temperature rise in the tower, given in Table 4, shows that among vertical shafts, the service shaft had by far the greatest temperature increase, with an average rise of 100°F (38°C). Pressure differences in the tower given in Table 5 show that, as expected, the greatest pressure differences occurred across the walls of the service shaft with flow from the floor spaces into the service shaft below the fifth floor and the reverse flow direction above it. A similar flow pattern can be seen for the return air shaft, but the pressure differences are much lower than those of the service shaft. It would appear that the service shaft acted as a flue and was the main passageway for CO_2 to migrate to upper floors, causing a tendency for CO_2 on these floors to enter the stair and elevator lobbies.

After 15 minutes of elevator shaft pressurization, as shown in Table 2, the elevator shaft was cleared of CO_2 but the levels of CO_2 in the elevator lobbies were still above critical level. Similarly, as shown in Table 3, when the lobby pressurization was activated, the lobbies were cleared of CO_2 but concentrations of CO_2 in the elevator shaft were above the critical level. A low-temperature fire test with the lobby pressurization system activated prior to ignition was successful in keeping the elevator shaft and lobbies smoke-free as long as all doors were kept closed. These results indicate that it is important to activate the pressurization system before the elevator shaft and lobbies are heavily contaminated with smoke. Tables 2 and 3 also show that, as expected, CO_2 concentrations in the un-

TABLE 6

Results of Fire Tests with Elevator Shaft Pressurization Elevator lobby on fire floor (2nd floor)

	Temperature		Δ *P* lobby wall in of water (Pa)			CO_2 % absolute
	outside lobby °F (°C)	inside lobby °F (°C)	1.33 ft (0.40 m)	6.33 ft (1.93 m)	10.12 ft (3.08 m)	
			reference pressure—burn area			
Low Temp. Fire 840 °F (450° C)						
Pressurization	-	-	0.046 (11.5)	0.046 (11.5)	0.048 (11.9)	
Burn—30 min.	760 (405)	153 (67)	0.026 (6.5)	−0.004 (−1)	−0.026 (−6.5)	2.20
Burn + Press.—15 min.	673 (356)	91 (33)	0.081 (20.2)	0.051 (12.7)	0.017 (4.2)	0.12
Burn + Press. & open doors on ground floor—15 min.	716 (380)	116 (47)	0.055 (13.7)	0.010 (2.5)	−0.019 (−4.7)	0.20
High Temp. Fire 1380 °F (750° C)						
Pressurization	-	-	0.102 (25.4)	0.100 (24.9)	0.098 (24.4)	
Burn—30 min.	1243 (673)	460 (238)	0.006 (1.5)	−0.018 (−4.5)	−0.030 (−7.5)	2.94
Burn + Press.—15 min.	1070 (576)	145 (63)	0.140 (34.9)	0.100 (24.9)	0.094 (23.4)	0.25
Burn + Press. & open doors on ground floor—15 min.	1217 (630)	159 (87)	0.030 (7.5)	0.101 (2.5)	−0.010 (−2.5)	0.75

TABLE 7

Results of Fire Tests with Elevator Shaft Pressurization Elevator lobby on fire floor (2nd floor)

	Temperature		Δ *P* lobby wall in of water (Pa)			CO_2 % absolute
	outside lobby °F (°C)	inside lobby °F (°C)	1.33 ft (0.40 m)	6.33 ft (1.93 m)	10.12 ft (3.08 m)	
			reference pressure—burn area			
Low Temp. Fire 840 °F (450° C)						
Pressurization	-	-	0.053 (13.2)	0.051 (12.7)	0.050 (12.5)	
Burn + Press.—15 min.	656 (347)	98 (37)	0.087 (21.7)	0.053 (13.2)	0.020 (5.0)	0.04
Burn + Press. & open doors on ground floor—15 min.	664 (351)	100 (38)	0.052 (12.9)	0.013 (3.2)	−0.018 (−4.48)	1.4
High Temp. Fire 1380 °F (750° C)						
Pressurization	-	-	0.097 (24.1)	0.100 (24.9)	0.100 (24.9)	
Burn—30 min.	1230 (667)	390 (199)	0.013 (3.2)	−0.033 (−8.2)	−0.040 (−10.0)	0.90
Burn + Press.—15 min.	945 (496)	125 (52)	0.158 (39.3)	0.120 (29.9)	0.075 (18.7)	0.04
Burn + Press. & open doors on ground floor—15 min.	1106 (597)	140 (60)	0.069 (17.2)	0.023 (5.7)	−0.018 (−4.5)	0.10

pressurized stairwell increased when the elevator pressurization systems were activated.

Temperature, Pressure Difference, and CO_2 Concentration of the Second Floor Lobby Due to Fire

Tables 6 and 7 give the temperatures inside and outside the second floor elevator lobby, the pressure differences across the lobby wall, and the CO_2 concentrations inside the lobby. They show that when the burners are operating, the elevator lobby temperatures are well above the danger level for human exposure. The two walls of the lobby that are exposed to the burn area are constructed of a layer of 5/8 in (16 mm) thick gypsum wall board on either side of metal studs. With the pressurization system on, the lobby temperatures were lowered to about 90° to 100°F (33° to 37°C) for the low-temperature fire and to about 125° to 145°F (52° to 63°C) for the high-temperature fire. For the case when the shaft pressurization was activated before the burn period, the lobby temperature for a low-temperature fire was 98°F (37°C).

Examination of the resultant pressure differences across the elevator lobby wall indicated that they were about 20% and 40% greater than the algebraic sum of the pressure difference due to pressurization and temperature effect of fire for the low- and high-temperature fires, respectively. The greater value for the high-temperature than for

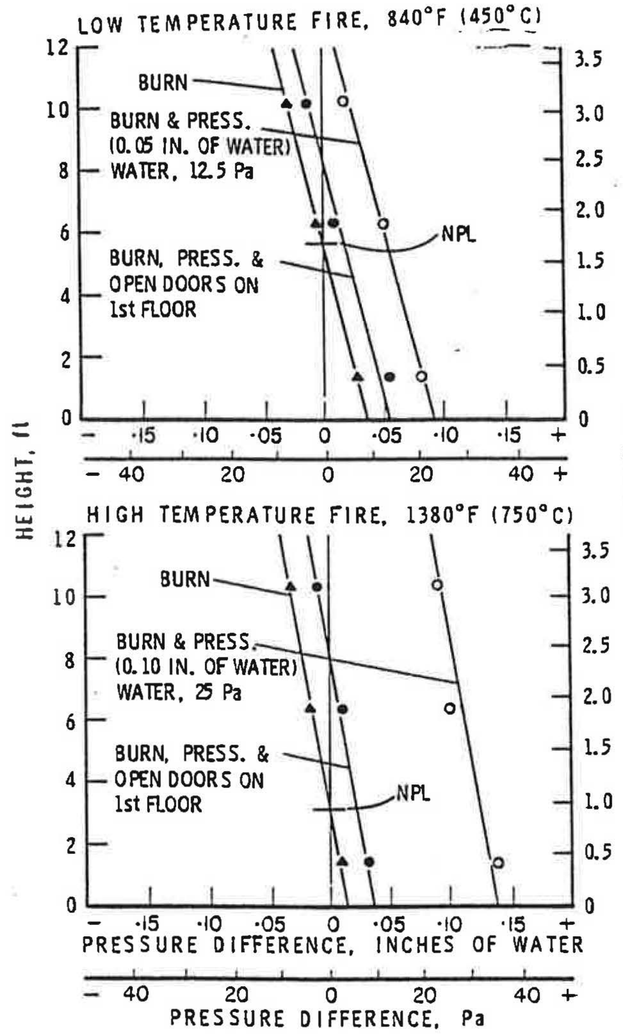


Figure 5 *Pressure differences across the walls of the second floor elevator lobby during fire tests with elevator shaft pressurization*

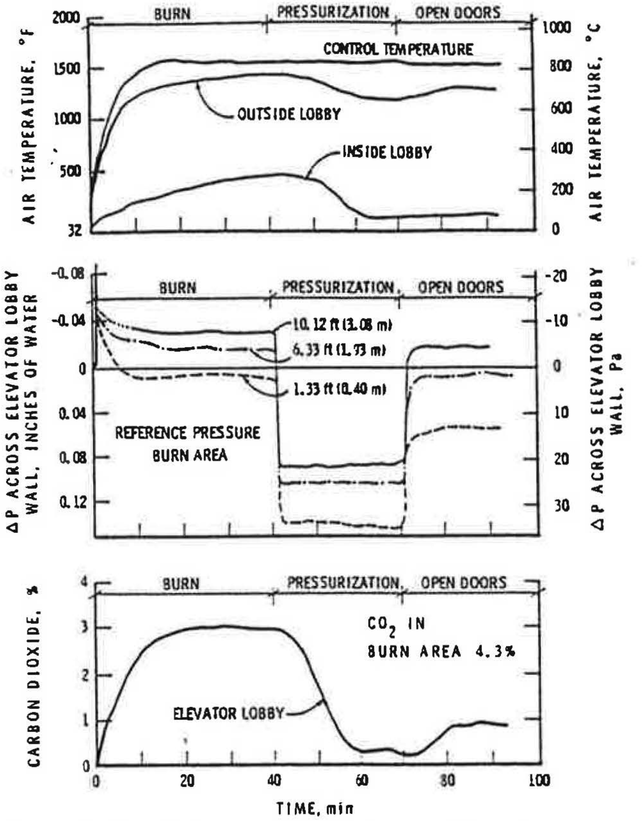


Figure 6 *Results of measurements in the second floor elevator lobby during a high-temperature fire test with elevator shaft pressurization*

the low-temperature fire may be attributed to the fire floor being vented to the outside for the former case, resulting in somewhat higher pressure differences on floors above and below the fire floor. It would appear that an amount of pressurization equal to the adverse pressure difference due to fire will likely be more than adequate to prevent smoke migration into the elevator lobby.

Figure 5 shows the pressure difference profile across the lobby wall for both the low- and high-temperature fires. For the low-temperature fire, the neutral pressure level (NPL) is located at about the 5.5 ft (1.6 m) level and for the high-temperature fire at the 3.2 ft (0.9 m) level. The location of the NPL depends on both the distribution of leakage openings on the fire floor and the gas temperatures. The lower NPL for the high-temperature fire is due to the lower gas density outside the elevator lobby than for the low-temperature fire. The maximum adverse pressure differences of 0.026 in of water (6.5 Pa) and 0.030 in of water (7.5 Pa) for the low- and high-temperature fires, respectively, occurred near the ceiling level of the lobby wall. When the mechanical pressurization was activated, the pressure profile shifted to the right to show positive pressurization for the full height of the lobby, but when the elevator, lobby, and exit doors on the ground floor were opened, it shifted to the left to underpressurize the upper walls of the lobby.

The variation of lobby temperature, pressure difference, and CO_2 concentration during the burn, pressurization, and open-door periods are graphically illustrated in Figure 6. The time-lobby pressure difference curve shows that soon after ignition of the burners, there is a sudden momentary increase in adverse pressure difference, probably caused by the rapid thermal expansion of gases to 0.05 in of water (12.5 Pa) with a spike of 0.085 in of water (21 Pa) and a decrease to a steady value as the burn area reached the control fire temperature. For the low-temperature fire, thermal expansion caused a maximum pressure difference of 0.06 in of water (15 Pa) with a spike of 0.10 in of water (25 Pa). A higher thermal expansion effect occurred with the low- as compared to the high-temperature fire, probably because for the former, only one burner strip was used, whereas for the latter, three burner strips were ignited in sequence. Pressure differences due to thermal expansion, which were of short duration, did not cause significant concentration of CO_2 in the elevator lobby in the case of the low-temperature fire with the lobby directly pressurized to 0.05 in of water (12.5 Pa) prior to igniting the burner. The supply air for pressurization probably diluted smoke that might have infiltrated the lobby.

Examination of CO_2 concentrations in the elevator lobby, as given in Tables 6 and 7, shows that the CO_2 concentrations were reduced significantly with shaft pressurization (see also Figure 6) and reduced to the background level with lobby pressurization, but CO_2 levels in the lobby and elevator shaft increased for both the shaft and lobby pressurization when the doors on the ground floor were opened.

Comparison of Calculated and Experimental Results

The results of the tests conducted to check the equations in Appendix A, developed for the design of pressurization systems with pressure control, are summarized in Table 8. For both the variable supply air and relief dampers for pressure control, the measured and calculated values of supply air rates and pressure differences agreed well within 10% of each other. To facilitate comparison of the calculated and measured values, the supply air rate for elevator pressurization was kept constant with closing or opening of the doors on the ground floor. In practice, the supply air rate, according to the fan characteristic, would decrease with the closing of doors due to the increase in the system's flow resistance, and the opposite would occur with the opening of doors; hence, assuming a constant supply air rate would give conservative values of pressure difference across the elevator lobby wall.

The leakage openings at the top of the elevator shaft were not considered in the calculation. Measurements by Tamura and Shaw (1976) in several buildings indicated that they varied from 4 to 10 ft² (0.37 to 0.93 m²), except for one case of 0.50 ft (0.046 m²) in which openings in the concrete floor slab of the machine room were partly covered with sheet metal. The leakage openings at the top of a pressurized elevator shaft should be minimized or taken into account in the calculation of supply air rates and size of relief dampers. Using the equation in Appendix A, step 4, for an open elevator door with Ao replaced by the leakage area at the top of an elevated shaft will give conservative values.

Elevator, Lobby, and Exit Doors

The examples shown in Table 8 are for the cases with all doors closed and with elevator, lobby, and exit doors open on the ground floor. For the case of a variable air supply pressurization system, the pressure difference across the elevator lobby was intended to be controlled to 0.05 in of water (12.5 Pa) for a low-temperature fire. The required supply air rate for elevator shaft pressurization ranged from 2000 to 5590 cfm (0.944 to 2.64 m³/s); if the lobby doors on all floors except the fire floor were also assumed to be open, the required maximum supply air rate would have been 5950 cfm (2.82 m³/s). For the case of a pressurization system with relief dampers to maintain the same pressure difference as in the case with the ground floor doors open, but to 0.15 in of water (37.5 Pa) with all doors closed, the required damper sizes were 0.21 ft² (0.020 m²) and 0.11 ft² (0.011 m²) for the elevator shaft and lobby pressurization systems, respectively. To maintain the pressure difference at 0.05 in of water (12.5 Pa) with all doors closed, larger relief dampers would be required and they can be calculated using equations in Appendix A, step 9, with $L = 1.0$. For this case, the required damper sizes in the shaft walls would be 0.62 ft² (0.057 m²) and 0.67 ft² (0.063 m²) for the shaft and lobby pressurization systems, respectively. Furthermore, if the lobby doors on all floors except the fire floor were assumed also to be open, the required damper sizes would be 0.68 ft² (0.063 m²) in the shaft wall for the shaft pressurization system.

CONCLUSIONS

1. Fire tests conducted in the experimental fire tower indicated that the tower was completely contaminated with smoke (CO_2 as indicator) due to effect of the fire temperature alone. The elevator shaft pressurization system was effective in clearing smoke in the shaft in a short time, but

TABLE 8

Comparison of the Calculated and the Measured Values of Supply Air Rates and Pressure Differences across the Elevator Lobby for Pressure Control of Elevator Pressurization Systems

Note: comparison indicated by underlined numbers

	Elevator shaft		**Pressurization**		**Elevator lobby**		**Pressurization**	
Method of pressure control	**Q_T, cfm (m^3/s)**		**ΔP_3, in of water (Pa)**		**Q_T, cfm (m^3/s)**		**ΔP_3, in of water (Pa)**	
	Calc.	**Meas.**	**Calc.**	**Meas.**	**Calc.**	**Meas.**	**Calc.**	**Meas.**
Variable Supply Air								
all doors closed	2000 (0.944)	2030 (0.958)	0.050 (12.5)	0.050 (12.5)	1980 (0.934)	2050 (0.968)	0.050 (12.5)	0.050 (2.5)
1st floor elevator, lobby and exit doors open	5590 (2.64)	5620 (2.65)	0.050 (12.5)	0.050 (12.5)	4440 (2.09)	4670 (2.20)	0.050 (12.5)	0.050 (12.5)
Relief Dampers*								
1st floor elevator, lobby and exit doors open	5590 (2.64)	5620 (2.65)	0.050 (12.5)	0.050 (12.5)	4440 (2.09)	4670 (2.20)	0.050 (12.5)	0.050 (12.5)
All doors closed	5590 (2.64)	5620 (2.65)	0.150 (37.5)	0.156 (36.1)	4440 (2.09)	4670 (2.20)	0.150 (37.5)	0.142 (35.4)

*Size of relief dampers for elevator shaft pressurization, 0.21 ft², (0.019 m²)
for elevator lobby pressurization, 0.11 ft² (0.011 m²)

residual smoke with concentrations above the critical level remained in the lobbies and, similarly, the elevator lobby pressurization system was effective in clearing smoke in the lobbies in a short time, but residual smoke remained in the shaft for some time. It is important to activate the pressurization systems before the elevator shaft and lobbies are heavily contaminated with smoke.

2. Examination of the pressure differences due to mechanical pressurization and those due to the fire indicated that an amount of pressurization equal to the adverse pressure difference caused by the fire will likely be more than adequate to prevent smoke migration into elevator lobbies. Test results indicated that at steady fire temperature, maximum adverse pressure differences due to the thermal effect of fire occurred across the elevator lobby wall at the ceiling level of about 0.026 in of water (6.2 Pa) for the low-temperature fire and 0.03 in of water (7.5 Pa) for the high-temperature fire. Those due to thermal expansion soon after ignition were much higher but of short duration. It is likely that a pressurization across the elevator lobby wall of 0.05 in of water (12.5 Pa) and 0.10 in of water (25 Pa) would be sufficient for low and high-temperature fires, respectively. Adverse pressure differences caused by other mechanisms, however, should also be considered in the design.

3. Opening elevator, lobby, and exit doors on the ground floor caused a reduction in pressurization resulting in the contamination of the elevator shaft and lobby on the fire floor. To cope with open-door situations, equations were developed to permit the design of pressurization systems with variable supply air with feedback control and also with relief dampers. These equations gave results that were well within 10% of the measured values in the experimental fire tower. It should be emphasized, however, that to design an effective pressurization system requires a knowledge and control of the air leakage characteristics of the building and, in particular, those of the elevator shaft and lobbies.

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APPENDIX A

Calculation of Pressures, Flow Rates, and Vent Sizes

The following equations were derived for the elevator shaft and lobby pressurization systems, which are illustrated in Figures 4a and 4b, respectively, by applying the equations for parallel/series flow and airflow through leakage openings, which are given in Klote and Fothergill (1983).

	Pressurized Elevator Shaft	**Pressurized Lobbies**
1. Ae, overall equivalent leakage area from the pressurized space to outside	$\frac{(A_1 + A_{23e})A_4}{[(A_1 + A_{23e})^2 + A_4^2]^{1/2}}$ where $A_{23e} = \frac{A_2 A_3}{(A_2^2 + A_3^2)}$ note: with lobby door open $(A_3 \quad A_2)$ $A_{23e} = A_2$	$\frac{(A_{12e} + A_3)A_4}{[(A_{12e} + A_3)^2 + A_4^2]^{1/2}}$ where $A_{12e} = \frac{A_1 A_2}{(A_1^2 + A_2^2)^{1/2}}$ note: with lobby open A_3 = leakage area due to door opening Vertical flow in shaft assumed to be negligible.
2. ΔP, overall pressure difference from the pressurized space to outside	where ΔP_3 = pressure difference across the elevator lobby door	
3. Q_f, pressurization flow rate per floor	where $M = \Delta P_3/\Delta P$ (see Step 2) For air at standard condition $C = 2400$ with Q (cfm), A_e (ft^2), ΔP_3 (in of water) $C = 772$ with Q (L/s), A_e (m^2), ΔP_3 (Pa)	
4. Q_o, flow rate at ground floor through open elevator door with lobby and entrance doors also open	where A_o = leakage area of an open elevator door N = total number of floors	
5. Q_T', total required pressurization flow rate for a given ΔP_3 with all doors on ground floor of Step 4 closed	$N\,Q_f$	$N\,Q_f$
6. $\Delta P_3'$; Q_T with ground floor elevator, lobby, and entrance doors open		
7. Q_T', total required flow rate for a given $\Delta P_3'$ with ground floor	$(N - 1)Q_f + Q_o$	$(N - 1)Q_f + Q_o$

elevator, lobby, and entrance doors open		
8. ΔP_3; Q_T' with all doors closed	Shaft wall	Shaft wall
9. A_d, required size of relief damper for each floor in the wall of the elevator shaft/lobby for a factor L		
	where	$A_d = A_1' - A_1$
	L = allowable factor for increase in ΔP_3 when open doors on ground floor are closed	Lobby wall
10. Q_{dT}, required total supply air rate with relief dampers	Q_T'	Q_T'

APPENDIX B

Pressures, Flow Rates, and Vent Sizes for the 10-Story Experimental Fire Tower

Leakage Areas

A_1 = 0.07 ft^2 (0.006 m^2);
A_2 (elevator door closed) = 0.75 ft^2 (0.070 m^2);
A_2 (elevator door open) = 6.00 ft^2 (0.557 m^2);
A_3 = 0.30 ft^2 (0.028 m^2);
A_4 = 0.79 ft^2 (0.073 m^2)

	Pressurized Elevator Shaft	Pressurized Lobbies
1. A_e (per story)	0.318 ft^2 (0.0295 m^2)	0.335 ft^2 (0.0311 m^2)
2. ΔP	1.39 ΔP_3	1.22 ΔP_3
3. Q_f	900 (ΔP_3) cfm	888 (ΔP_3) cfm
	26.4 $(\Delta P_3)^{1/2}$ ℓ/s	26.0 $(\Delta P_3)^{1/2}$ ℓ/s
4. Q_o	16980 $(\Delta P_3)^{1/2}$ cfm	11900 $(\Delta P_3)^{1/2}$ cfm
	507 $(\Delta P_3)^{1/2}$ ℓ/s	355 $(\Delta P_3)^{1/2}$ ℓ/s
5. Q_T	9000 $(\Delta P_3)^{1/2}$ cfm	8880 $(\Delta P_3)^{1/2}$ cfm
	264 $(\Delta P_3)^{1/2}$ ℓ/s	265 $(\Delta P_3)^{1/2}$ ℓ/s
6. $\Delta P_3'$; (Q_T)	0.13 ΔP_3	0.20 ΔP_3
7. Q_T'	25000 $(\Delta P_3)^{1/2}$ cfm	19900 $(\Delta P_3)^{1/2}$ cfm
	745 $(\Delta P_3)^{1/2}$ ℓ/s	590 $(\Delta P_3)^{1/2}$ ℓ/s
8. ΔP_e; (Q_T')	7.7 ΔP_3	5.0 ΔP_3
	Shaft wall	**Lobby wall**
9. A_d; $(L = 3)$	0.21 ft^2 (0.020 m^2)	0.11 ft^2 (0.010 m^2)
		Shaft wall
		0.11 ft^2 (0.010 m^2)
10. Q_{dT}	same as 7	same as 7

DISCUSSION

C. ROUSSEAU, Newcomb & Boyd, Atlanta, GA: Have you run into the problem of leaky elevator shaft construction vs. tight exterior building construction and the inability of the shaft pressurization to maintain pressure difference between the shaft and the occupied space?

KLOTE: When considering the possible use of elevators for fire evacuation, the pressure difference of interest is not between the shaft and the building but between the elevator lobby and the building. For an elevator system to be considered for fire evacuation, the elevator lobbies must be protected from smoke during evacuation. The leakage areas around a number of elevator doors were measured by Tamura and Shaw and reported in a paper published in *ASHRAE Transactions 1976* entitled "Air Leakage Data for Design of Elevator and Stair Shaft Pressurization Systems." For these few tests the leakage area around a closed elevator door was in the range of ½ to ¾ square feet. This was for double opening elevator doors which are the most common. It is easy to observe that the gaps around most elevator doors are large. For the elevator smoke control systems envisioned in buildings, the leakage area from the shaft to the lobby is much greater than that from the lobby to the building. This means that the pressure difference between the lobby and the shaft is very small while the pressure difference between the lobby and the building is much larger. Thus we can maintain a large pressure difference across the elevator lobby doors even if the gaps around the elevator doors are very large. The advantage of this is that the most commonly used elevator doors that have large gaps can be used without modification. Further, leakage areas between the elevator door frame and the walls are not a concern. The high leakage areas from the shaft to the lobby are especially useful when the elevator lobby is indirectly pressurized by air supplied to the shaft. For the systems we are talking about, tight fitting elevator doors should be avoided.

ROUSSEAU: Where is the preferable location to inject air into shaft?

G. JOLETTE, AMCA, Arlington Heights, IL: Where should fan be placed due to smoke on roof?

TAMURA: To minimize the possibility of smoke ingestion, the preferred location of the fan is near ground level. Also, during cold weather, the operation of the fan at this location will be assisted by stack action, whereas, on the roof, the reverse is the case.

JOLETTE: Was the example airflow rate for elevator and for the lobby intended to be a single flow?

TAMURA: The supply air for pressurization given in the paper were injected entirely either in the elevator shaft or in the elevator lobbies.