SMOKE CONTROL SYSTEMS FOR ELEVATOR FIRE EVACUATION

by John H. Klote and George T. Tamura

ABSTRACT

Some people cannot use stairwells because of physical disabilities, and for these people fire evacuation is a serious problem. A potential solution to this problem is the use of elevators for fire evacuation. A joint project of the U.S. National Institute of Standards and Technology (NIST) and the National Research Council of Canada (NRCC) was formed to evaluate the feasibility of using elevators for the evacuation of the handicapped during a fire. This project consisted of conceptual studies, full scale fire experiments, and theoretical analysis. This paper summarizes the findings of the joint project that are relevant to the design of smoke control systems for elevators. A method of dealing with elevator piston effect is discussed. All other things being equal, piston effect is considerably greater for single car hoistways than for multiple car hoistways. Different approaches to deal with the pressure fluctuations due to opening and closing of building doors are presented. A method of design analysis is presented with an example analysis. Results indicate that many types of elevator smoke control systems can be designed to provide acceptable levels of pressurization even under severe conditions of doors opening and closing.

NOMENCLATURE

A area
C flow coefficient for flow path, dimensionless
C_c flow coefficient for flow around car, dimensionless
g acceleration of gravity
h height above neutral plane
m mass flow rate
P absolute pressure
R gas constant
T absolute temperature
V elevator car velocity
Δp pressure difference
ρ air density

Subscripts

a free flow area in shaft around elevator car
crit critical pressure difference from the elevator lobby to the outside
e effective
f fire
i building
o outside
r elevator lobby
s hoistway (elevator shaft)

1.0 INTRODUCTION

Throughout most of the world, there are signs next to elevators indicating they should not be used in fire situations; stairwells should be used for fire evacuation. These elevators are not intended as means of fire egress, and they should not be used for fire evacuation (Sumka, 1987). However, some people cannot use stairwells because of physical disabilities, and for these people fire evacuation is a serious problem. The use of elevators is a potential solution to this problem. Logistics of evacuation, reliability of electric power, elevator door jamming, water damage to electric controls, and fire and smoke protection are long-standing obstacles to the use of elevators for fire evacuation. All of these obstacles except smoke protection can be addressed by existing technology (Klote, 1983).

A joint project of the National Institute of Standards and Technology (NIST) in the United States and the National Research Council of Canada (NRCC) was formed to evaluate the feasibility of using elevators for the evacuation of he handicapped during a fire. Full-scale fire xperiments were conducted at the NRCC's ten tory fire research tower near Ottawa (Tamura and lote, 1988, 1987a, 1987b, 1987c). These xperiments verified that pressurization can rovide smoke protection for the elevator system. dditionally, the joint NIST/NRCC project ddressed the impact of pressure disturbances aused by elevator car motion on smoke control Klote and Tamura, 1987, 1986b; Klote, 1988). uch piston effect is a concern, because it can pull moke into a normally pressurized elevator lobby. his paper summarizes the findings of the joint roject that are relevant to the design of smoke ontrol systems for elevators.

2.0 PISTON EFFECT

Analysis of the air flows and pressures roduced by elevator car motion in a pressurized oistway was developed by Klote (1988), based on ontinuity equation for the contracting control olume in hoistway (elevator shaft) above an scending car. Based on this analysis, the pressure ifference from the elevator lobby to the building t which piston effect cannot overcome lobby ressurization is the critical pressurization, Δp_{crit}, nd is expressed as

$$\Delta p_{crit} = \frac{\rho_s}{2}\left(\frac{A_e\, A_s\, V}{A_{ri}\, A_a\, C_c}\right)^2 \qquad (1)$$

here ρ_s, A_s, A_{ri}, A_a, V, and C_c are the air density the hoistway, cross sectional area of the oistway, leakage area between the lobby and the uilding, the free area around the elevator car, the ir velocity, and the flow coefficient for flow ound the elevator car. The effective area, A_e, is

$$A_e = \left(\frac{1}{A_{sr}^2} + \frac{1}{A_{ri}^2} + \frac{1}{A_{io}^2}\right)^{-\frac{1}{2}} \qquad (2)$$

here A_{sr} is the leakage area between the hoistway d the lobby, and A_{io} is the leakage area between e building and the outside. The example analysis esented later addresses piston effect.

3.0 SYSTEM CONCEPT

Smoke control systems for elevator evacuation ust provide smoke protection for elevator lobbies, hoistways (elevator shafts), and machinery rooms. Protection of lobbies is essential so that people will have a safe place to wait for the elevator. Protection of the machinery room is important to prevent damage to elevator machinery. Figure 1 illustrates a system that pressurizes the hoistway directly and indirectly pressurizes the elevator lobby and the machinery room. The hoistway vent is not shown, but this topic is addressed later in this paper.

3.1 Hoistway Pressurization and Lobby Pressurization

Considering the leakage from the elevator lobby to the outside to be negligible, the mass flow rate from the hoistway to the elevator lobby equals the flow from the lobby to the building space

$$m = C_{sr} A_{sr}\sqrt{2\rho_{sr}\Delta p_{sr}} = C_{ri} A_{ri}\sqrt{2\rho_{ri}\Delta p_{ri}} \qquad (3)$$

where m, C, A, ρ, and Δp are the mass flow rate, flow coefficient, area, density, and pressure difference. The subscripts s, r, and i are for the hoistway, the elevator lobby, and the building space. Considering $\rho_{sr} = \rho_{ri}$ and $C_{sr} = C_{ri}$, equation (3) leads to

$$\frac{\Delta p_{sr}}{\Delta p_{ri}} = \left(\frac{A_{ri}}{A_{sr}}\right)^2 \qquad (4)$$

For elevator doors with wide gaps that are common in most buildings, Tamura and Shaw (1976) showed that the leakage area of the gaps is generally in the range of 0.5 to 0.7 ft^2 (0.05 to 0.07 m^2). Based on general experience with building leakages (Klote and Fothergill, 1983), A_{ri}/A_{sr} is therefore about 0.4 for construction of average tightness and about 0.1 for tight construction. From equation (4), $\Delta p_{sr}/\Delta p_{ri}$ is 0.16 and 0.01 for average and tight construction. Thus, the pressure in the elevator lobby can be expected to be close to the pressure in the hoistway, provided that the construction is not unusually leaky. Pressurization air can be supplied to the elevator lobbies (figure 2). However, from the above discussion it seems that this direct lobby pressurization does not result in any significant improvement in pressurization over supplying the air into the hoistway as illustrated in figure 1.

Direct lobby pressurization has some advantage over direct hoistway pressurization in purging small amounts of smoke from the lobby. Part of the

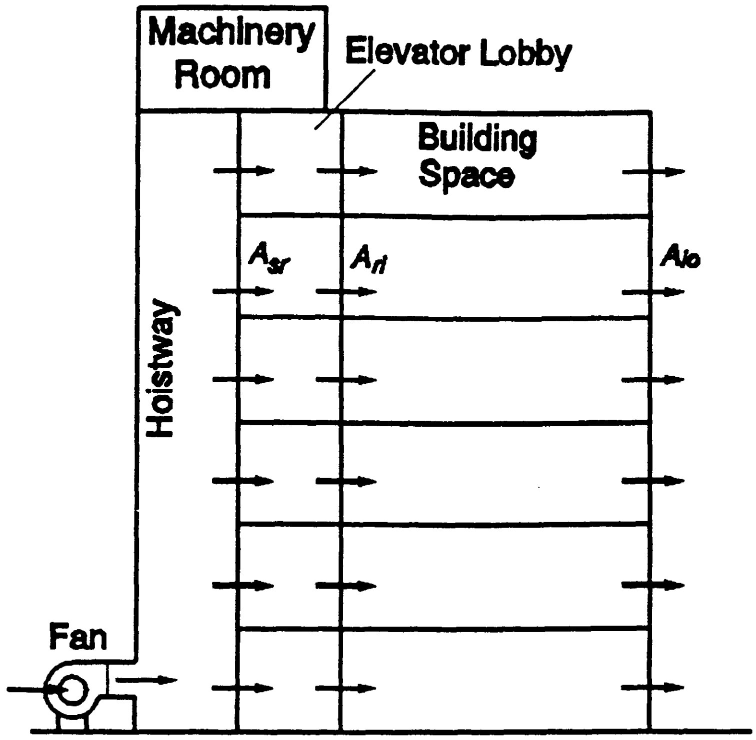

FIG. 1 ELEVATOR SMOKE CONTROL BY SHAFT PRESSURIZATION

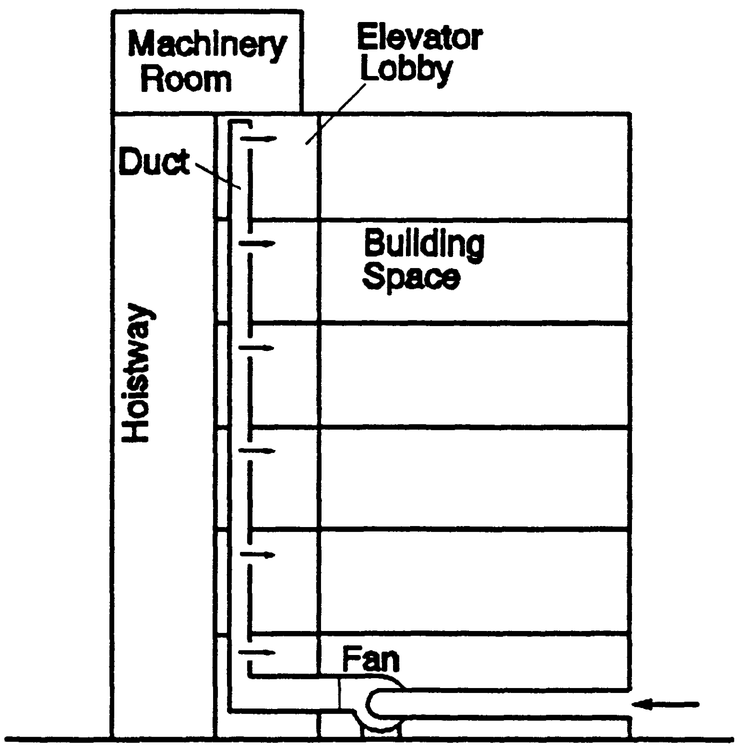

FIG. 2 ELEVATOR SMOKE CONTROL BY LOBBY PRESSURIZATION

ressurization air to an elevator smoke control ystem goes from the hoistway to the outside, and he rest goes from the lobby through the building o the outside. With direct lobby pressurization, oth these amounts flow through the lobby. Such n increased flow rate tends to better purge any mall amounts of smoke that would get into the obby before smoke control activation or when a erson is entering the lobby. The relative benefit f this improved purging compared to its cost has ot been evaluated. The following discussions ave been focused arbitrarily on the hoistway ressurization systems.

.2 Pressure Fluctuations due to Open Doors

Elevator systems must be designed to maintain esign pressure differences under the likely onditions of opened and closed doors. Klote and amura (1986a) showed that opening a large flow ath from the pressurized spaces to the outside can esult in a significant loss in pressurization. For xample opening the elevator doors, elevator lobby oors, and exterior doors resulted in a pressure rop from 0.13 in H_2O (32 Pa) to 0.03 in H_2O (7 a) for a system without features to resist pressure luctuation.

During a fire, it is expected that several xterior doors will be propped open, and the levator doors will open and close as elevators are sed for evacuation. Further, stairwell doors are kely to be opened and closed as people use them r evacuation. It is envisioned that lobby doors ill close automatically upon smoke control system ctivation. However, lobby doors can be advertently blocked and the closing mechanism an fail. It is anticipated that occupants will close ny such opened lobby doors to prevent being xposed to smoke. Doors may not be closed on oors where there is no smoke danger or there are o people waiting in the elevator lobby. The noke control system should be designed to aintain pressurization when some elevator lobby oors are open on floors away from the fire. The xample analysis presented later addresses pressure uctuations due to opening and closing doors.

4.0 DESIGN PRESSURE DIFFERENCES

The maximum allowable pressure difference cross the lobby doors is a value that does not sult in excessive door opening forces. The force open a door can be calculated by a hydrostatic analysis of the moments on a door including the pressure difference across the door and the force of the door closer mechanism (Klote and Fothergill, 1983). The Life Safety Code (NFPA 1988a) states that the force required to open any door in a means of egress shall not exceed 30 lb (133 N). For a door closer force of 10 lbs (45 N) on a 36 inch (0.91 m) wide door, a pressure difference of 0.34 in H_2O (85 Pa) results in a door opening force of 30 lb (133N).

Besides the maximum value, a system should also operate above a minimum value sufficient to prevent smoke infiltration into the lobby. The design approach is for this minimum value to incorporate the fire effect of buoyancy, and account for other driving forces discussed in the analysis later. The pressure difference due to buoyancy of hot fire gases between a fire compartment and its surroundings is expressed as

$$\Delta p = \frac{g P h}{R} \left(\frac{1}{T_o} - \frac{1}{T_f} \right) \qquad (5)$$

where h is the height above a neutral pressure plane between the fire compartment and its surroundings. For a fire compartment temperature of 1700°F (930°C), the pressure difference 6.0 ft (1.82 m) above the neutral plane is 0.065 in H_2O (16 Pa). NFPA 92A (1988b) suggests a minimum value of 0.10 in H_2O (25 Pa) for an unsprinklered building with a ceiling height of 9 ft (2.74 m). This considers the neutral plane at 6 ft (1.82 m) below the ceiling, and allows a safety factor of 0.035 in H_2O (9 Pa). NFPA 92A also suggests a minimum value of 0.05 in H_2O (12.5 Pa) for sprinklered buildings.

5.0 SMOKE CONTROL SYSTEMS

Elevator smoke control systems can incorporate features to deal with pressure fluctuations due to opening and closing doors. These features include pressure relief vents, vents with barometric dampers, variable-supply air fans, fire floor venting, and fire floor exhaust.

5.1 Pressure Relief Vent System

This system has a "constant-supply" air rate fan and a pressure relief vent to the outside as illustrated in figure 3. The area of this vent is fixed, and sized for operation in the smoke control system. The vent can be fitted with automatic

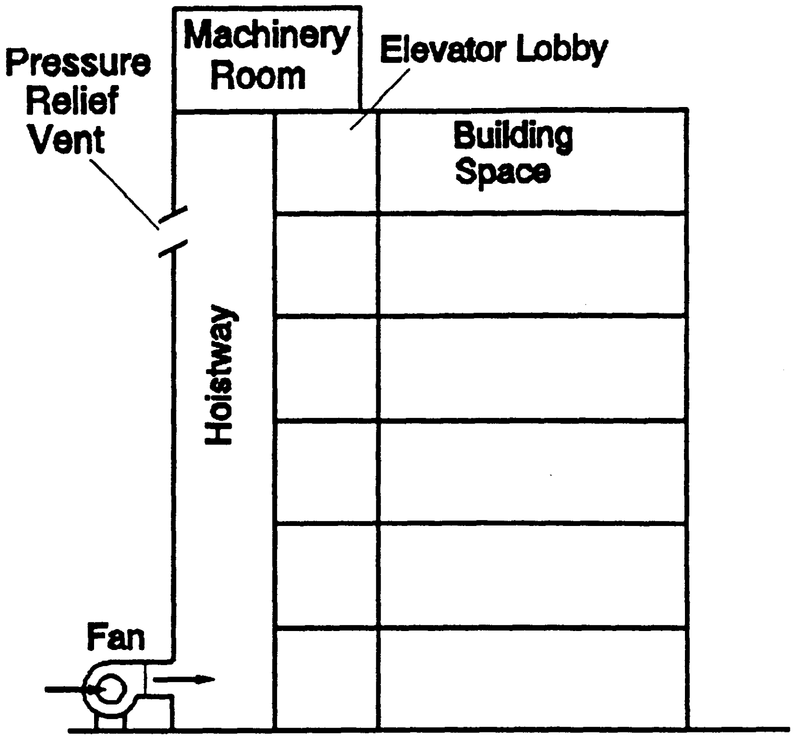

FIG. 3 ELEVATOR SMOKE CONTROL WITH A PRESSURE RELIEF VENT

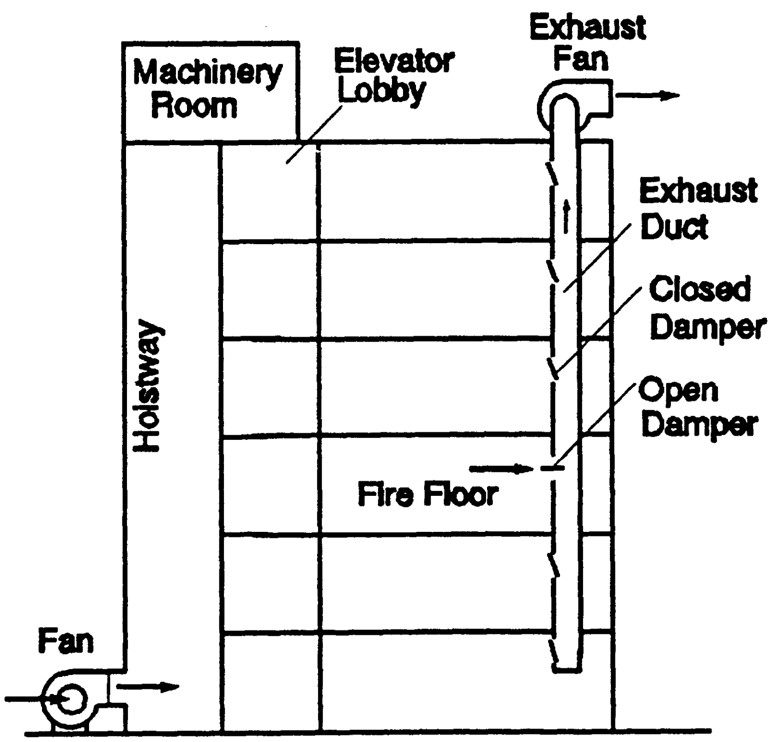

FIG. 4 ELEVATOR SMOKE CONTROL WITH FIRE FLOOR EXHAUST

dampers, if it is desired for it to be normally closed. The supply rate varies to some extent with the pressure across the fan, but the term "constant-supply" is used to differentiate this fan from one that has a "variable-supply" rate. The vent must be large enough that the maximum allowable pressure difference is not exceeded when all doors are closed. When paths to the outside are opened, air flows through them and the hoistway pressure drops. This system must maintain at least the minimum allowable pressure difference when some design combination of paths is open.

5.2 Barometric Damper System

This system is similar to the one above, except that the vent has a barometric damper which closes when the pressure drops below a specified value. The use of these dampers minimizes air losses when paths from the elevator shaft are opened, and therefore helps the system maintain pressure.

5.3 Variable-Supply Air System

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 of supply air to the hoistway. The variable flow fans are controlled by one or more static pressure sensors that sense the pressure difference between the lobby and the building. When paths from the smoke control system are opened, the pressure drops and the flow rate of supply air is increased to achieve at least the minimum allowable pressure difference. When the paths are closed, the pressure in the elevator system increases and the flow rate is reduced to prevent excessive pressure differences.

5.4 System with Fire Floor Venting or Exhaust

Smoke venting and smoke exhaust of the fire floor can improve system performance. The venting or exhaust increases the pressure difference from the lobby to the fire floor. The vents can be exterior wall vents or non-powered smoke shafts. Figure 4 shows a fan-duct system intended to exhaust the fire floor. Upon detection of fire or smoke, the damper opens on the fire floor and the exhaust fan is activated. The detection system must be configured to identify the fire floor.

6.0 ANALYSIS OF SMOKE CONTROL SYSTEMS

The design of an elevator smoke control system includes selection of a system for dealing with pressure fluctuations, determining appropriate values for leakage areas and other parameters, as well as calculating the performance of the smoke control system. The following section discusses a computer program that can be used for analysis of these systems. This program evaluates the effects of outside temperature, forced ventilation, and the wind. The example analysis that is provided does not address the effects of wind. A wind of 50 mph (22 m/s) results in a velocity pressure on the order of 1 in H_2O (250 Pa). However, occurrence of such high velocity wind is infrequent and should not pose a problem provided that windows do not brake. Further, the likelyhood of the fire resulting in broken windows is considered to be much lower for a sprinklered building than an unsprinklered one.

6.1 Network Computer Program

Elevator smoke control systems can be analyzed by a computer program such as the one presented by Klote and Fothergill (1983). 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 and stairwells are modeled by a series of vertical spaces, one for each floor. Air flows through openings from regions of high pressure to regions of low pressure. The mass flow rate to space i from space j is expressed as

$$m_{ij} = S\, C_{ij}\, A_{ij} \sqrt{2\ \rho\ |p_j - p_i|} \qquad (6)$$

where m, C, A, and p are mass flow rate, flow coefficient, area, and pressure, and the subscripts i and j refer to spaces i and j. S is the sign of (p_j - p_i), and ρ is the density of the gas in the path connecting the two spaces. Space j may be another location within the building or it can be outside the building. An outside pressure p_j is dependent only on the outside air temperature and wind effects. For a building space i with connections to k other spaces, the steady flow conservation of mass equation is

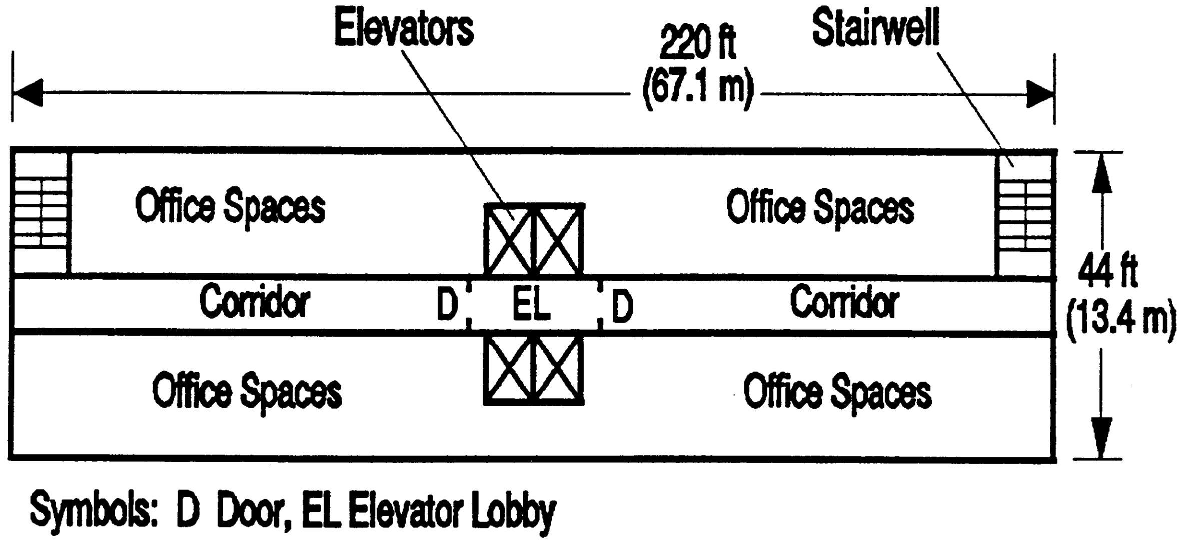

FIG. 5 TYPICAL FLOOR PLAN (ABOVE FIRST FLOOR) OF EXAMPLE BUILDING

$$\sum_{j=1}^{k} m_{ij} = 0 \qquad (7)$$

In general the mass flows are described by equation (6), but the effects of forced ventilation are incorporated by use of a constant mass flowterm to a ventilation space j. By substitution of equation (6) into equation (7), a system of equations is obtained for all n spaces.

$$f_1(p_1, p_2, \ldots, p_n) = 0$$
$$\vdots$$
$$f_i(p_1, p_2, \ldots, p_i, \ldots, p_n) = 0 \qquad (8)$$
$$\vdots$$
$$f_n(p_1, p_2, \ldots, p_n) = 0$$

The building pressures, p_1 to p_n, are solved simultaneously by solving n non-linear mass balance equations. In reality, the only pressures included in the equation for space i ($f_i = 0$) are those of space i and those of spaces directly connected to it. Using these pressures, the mass flow rates throughout the network are calculated by equation (6). The computer prints out the mass flow rates and pressures for all n spaces.

6.2 Example Computer Analysis

An eleven-story building with a typical floor plan shown in figure 5 was selected arbitrarily for this example. Because the building is symmetric, only half of each floor was analyzed. The minimum and maximum allowable pressure differences for the system are 0.05 and 0.34 in H_2O (12 and 85 Pa). The other design parameters are listed in table 1. To deal with pressure fluctuations of opening and closing doors, the system incorporates a relief vent of 24 ft^2 (2.23 m^2). Pressurization air is supplied at 35,000 cfm (16.5 m^3/s) into the hoistway at the second floor.

Eight runs of the computer program were made for the conditions of open and closed doors listed in table 2. The resulting pressure differences from the lobby to the building are listed in tables 3 and 4. For this system, the pressure differences from the lobby to the building are always lower for winter temperatures than for summer temperatures. With all doors closed, the highest pressure difference is 0.26 in H_2O (65 Pa) in the summer (run 5). As expected when the first floor lobby doors and exterior doors are open, the flow

TABLE 1 PARAMETERS OF EXAMPLE SMOKE CONTROL SYSTEM

Flow Areas:	ft^2	m^2
First floor exterior wall (exterior doors closed)	0.940	0.0873
First floor exterior wall (exterior doors opened)	22.0	2.04
Exterior walls (except on 1st floor)	0.540	0.0502
Stairwell to building (stair door closed)	0.270	0.0251
Stairwell to building (stair door opened)	10.5	0.975
Building floor	0.270	0.0251
Building to elevator lobby (lobby doors closed)	0.42	0.0390
Building to elevator lobby (lobby doors opened)	22.0	2.04
Elevator lobby to hoistway (elevator door closed)	1.60	0.149
Elevator lobby to hoistway (elevator door opened)	8.00	0.743
Pressure relief vent from hoistway to outside at 8th floor	24.0	2.23
Other Parameters:		
Height between building floors	10.0 ft	0.929 m
Number of floors	11	11
Building air temperature	70°F	21°C
Winter outside temperature	5°F	-15°C
Summer outside temperature	90°F	32°C

TABLE 2 ARRANGEMENT OF DOORS FOR COMPUTER ANALYSIS OF EXAMPLE SMOKE CONTROL SYSTEM

Run	Season	1st Floor Exterior Door Open	Elevator Doors Open on Floors:	Elevator Lobby Doors Open on Floors:	Stairwell Doors Open on Floors[1]:
1	Winter	No	None	None	None
2	Winter	Yes	1	1	None
3	Winter	Yes	1	1, 10, 11	10, 11
4	Winter	Yes	1	1, 8, 9, 10, 11	8, 9, 10, 11
5	Summer	No	None	None	None
6	Summer	Yes	1	1	None
7	Summer	Yes	1	1, 10, 11	10, 11
8	Summer	Yes	1	1, 8, 9, 10, 11	8, 9 10, 11

[1]Exterior stairwell door on the ground floor is closed when no other stair doors are opened, and it is open when any other stair door is opened.

TABLE 3 COMPUTER CALCULATED PRESSURE DIFFERENCES FOR EXAMPLE SMOKE CONTROL SYSTEM IN ENGLISH UNITS

Run	Pressure Difference in inches H_2O from Elevator Lobby to Building on Floors:										
	1	2	3	4	5	6	7	8	9	10	11
1	0.18	0.18	0.17	0.16	0.15	0.14	0.13	0.12	0.12	0.13	0.13
2	Open	0.17	0.15	0.14	0.14	0.13	0.12	0.11	0.12	0.12	0.12
3	Open	0.15	0.13	0.12	0.11	0.10	0.09	0.08	0.08	Open	Open
4	Open	0.14	0.13	0.11	0.10	0.09	0.07	Open	Open	Open	Open
5	0.26	0.24	0.22	0.20	0.19	0.17	0.15	0.14	0.14	0.14	0.13
6	Open	0.23	0.20	0.19	0.17	0.16	0.14	0.13	0.13	0.13	0.12
7	Open	0.24	0.21	0.19	0.17	0.16	0.14	0.13	0.13	Open	Open
8	Open	0.22	0.19	0.17	0.15	0.14	0.12	Open	Open	Open	Open

TABLE 4 COMPUTER CALCULATED PRESSURE DIFFERENCES FOR EXAMPLE SMOKE CONTROL SYSTEM IN SI UNITS

Run	Pressure Difference in pascals from Elevator Lobby to Building on Floors:										
	1	2	3	4	5	6	7	8	9	10	11
1	45	45	42	40	37	35	32	30	30	32	32
2	Open	42	37	35	35	32	30	27	30	30	30
3	Open	37	32	30	27	25	22	20	20	Open	Open
4	Open	35	32	27	25	22	17	Open	Open	Open	Open
5	65	60	55	50	47	42	37	35	35	35	32
6	Open	57	50	47	42	40	35	32	32	32	30
7	Open	60	52	47	42	40	35	32	32	Open	Open
8	Open	55	47	42	37	35	30	Open	Open	Open	Open

TABLE 5 PARAMETERS FOR PISTON EFFECT EXAMPLE

A_s	121 ft^2	11.2 m^2
A_{rl}	0.420 ft^2	0.0390 m^2
A_a	79.8 ft^2	7.41 m^2
A_{sr}	1.60 ft^2	0.149 m^2
A_{io}	0.54 ft^2	0.0502 m^2
ρ_s	0.075 lb/ft^3	1.20 kg/m^3
V	500 ft/min	2.54 m/s
C_c	0.94	0.94

through this large path results in decreased pressurization. For this system, the resulting drop in pressurization is small (compare runs 1 and 2 or 5 and 6).

Another possible large path to the outside is through open lobby doors, through an open stairwell door, and out an open exterior stairwell door. This path was used on floors 10 and 11 (runs 3 and 7) and on floors 8, 9, 10, and 11 (runs 4 and 8). It is not likely that more than two of these paths would be open at one time, but four were used as a severe test of the system. The lowest pressure difference with four such paths open is 0.07 in H_2O (17 Pa) in the winter. Thus, the system is capable of maintaining pressurization within the allowable range.

6.3 Example Piston Effect Analysis

For the smoke control system of the above example, the parameters for analysis of piston effect are listed in table 5 for two cars in a hoistway. The elevator flow coefficient, C_c, was evaluated experimentally (Klote and Tamura, 1986b). From equation (2), the effective area, A_e, is 0.325 ft^2 (0.0302 m^2). From equation (1), the critical pressure is 0.024 in H_2O (6.0 Pa). For this example smoke control system, the lowest pressure difference with four such paths open (run 7) is 0.05 in H_2O (12 Pa) in the winter. Thus piston effect would not be a problem for this system.

All other things being equal, the critical pressure is higher for a single car hoistway than for a multiple car one. For a single car hoistway with A_s of 60.4 ft^2 (5.61 m^2), A_a of 19.4 ft^2 (1.80 m^2), C_c of 0.83 and other parameters listed in Table 5, equation (1) gives a critical pressure difference of 0.13 in H_2O (33 Pa). This pressure would be a concern for this smoke control system. Possible solutions include a slower car speed and use of another elevator with multiple cars in the hoistway.

7.0 CONCLUSIONS

(1) Elevator smoke control systems can be designed to provide acceptable levels of pressurization under severe conditions of doors opening and closing.

(2) While the example analysis was for a system with a pressure relief vent, other systems can be used to deal with the pressure fluctuations caused by doors opening and closing.

(3) Transient pressures produced by the motion of a car in a hoistway are of concern, because of the potential to pull smoke into an elevator lobby. All other things being equal, this elevator piston effect is considerably greater for single car hoistways than for multiple car hoistways. Equation (1) can be used to evaluate the extent of the piston effect problem.

8.0 REFERENCES

Klote, J.H. 1988. An Analysis of the Influence of Piston Effect on Elevator Smoke Control, Nat. Bur. Stand. (U. S.), NBSIR 88-3751.

Klote, J.H. 1983. Elevators as a means of Fire Escape, ASHRAE Transactions, Vol 89, Part 1B, pp 362-378.

Klote, J.H. and Fothergill, J.W. 1983. Design of Smoke Control Systems for Buildings, American Society of Heating, Refrigerating and Air-conditioning Engineers, Atlanta, GA.

Klote, J.H. and Tamura, G.T. 1987. Experiments of Piston Effect on Elevator Smoke Control, ASHRAE Transactions, Vol 93, Part 2, pp 2217-2228.

Klote, J.H. and Tamura, G.T. 1986a. Smoke Control and Fire Evacuation by Elevators, ASHRAE Transactions, Vol 92, Part 1A, pp 231-245.

Klote, J.H. and Tamura, G.T., 1986b. Elevator Piston Effect and the Smoke Problem, Fire Safety Journal, Vol 11, No 3, May, pp 227-233.

NFPA 1988a. Code for Safety to Life from Fire in Buildings and Structures, NFPA 101-1988, National Fire Protection Association, Inc., Quincy, MA, National Fire Protection Assn.

NFPA 1988b. Recommended Practice for Smoke Control Systems, NFPA 92A, Quincy, MA, National Fire Protection Assn.

Sumka, E.H. 1987. Presently, Elevators Are Not Safe in Fire Emergencies, ASHRAE Transactions, Vol 93, Part 2, pp 2229-2234.

Tamura, G.T. and Klote, J.H. 1987a. Experimental Fire Tower Studies on Elevator Pressurization Systems for Smoke Control, ASHRAE Transactions, Vol 93, Part 2, pp 2235-2257.

Tamura, G.T. and Klote, J.H. 1987b. Experimental Fire Tower Studies on Mechanical Pressurization to Control Smoke Movement Caused by Fire Pressures, Proceedings of the 2nd International Symposium on Fire Safety Science, Tokyo, Japan.

Tamura, G.T. and Klote, J.H. 1987c. Experimental Fire Tower Studies on Elevator Pressurization Systems for Smoke Control, ASHRAE Transactions, Vol 93, Part 2, pp 2235-2257.

Tamura, G.T. and Klote, J.H. 1988. Experimental Fire Tower Studies on Adverse Pressures Caused by Stack and Wind Action: Studies on Smoke Movement and Control, ASTM International Symposium on Characterization and Toxicity of Smoke, December 5, Phoenix, AZ.

Tamura, G.T. and Shaw, C.Y. 1976. Air Leakage Data for the Design of Elevator and Stair Shaft Pressurization Systems, ASHRAE Transactions, Vol 83 Part 2, pp. 179-190.

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