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Reprinted from
Fire Safety Journal
Vol. 11, No. 2, 1986
p. 227 - 233
(IRC Paper No. 1485)

Price $3.00

NRCC 28445

*Fire Safety Journal*, 11 (1986) 227 - 233



# Elevator Piston Effect and the Smoke Problem

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(Received May 1, 1986; in final form June 13, 1986)

## SUMMARY

*The material in this paper is part of a joint project between the United States and Canada to evaluate the feasibility of elevator evacuation of the handicapped. This paper presents an analysis for the pressure differences produced by elevator car motion and it presents flow coefficients for flow around cars in elevator shafts based on test data. The results of an experiment to verify this piston effect analysis are presented.* ***Also,*** *practical considerations concerning piston effect and elevator smoke control are presented. An equation is developed to determine the upper limit of the pressure difference across an elevator lobby caused by piston effect.*

## INTRODUCTION

In most elevator lobbies in North America, there are signs indicating that elevators should not be used in fire situations; rather that stairs should be used. Unfortunately, some people cannot use stairs because of physical handicaps. The use of elevators is a potential solution to these problems. Logistics of evacuation, reliability of electrical power, elevator door jamming, 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 adressed by existing technology as discussed by Klote [1].

The National Bureau of Standards (NBS) in the United States and the National Research Council of Canada (NRCC) are engaged in a joint project to develop smoke control technology for elevators. The initial report [2] of this project contained discussions and evaluations of elevator smoke control systems. The transient pressures due to 'piston effect' when an elevator car moves in a shaft is a concern of building designers relative to elevator smoke control. This paper addresses piston effect and evaluates it with respect to elevator smoke control. The term 'smoke control' is used to mean the limiting of smoke movement by pressurization produced by mechanical fans. This meaning has attained some level of acceptance in North America.

## ANALYSIS OF PISTON EFFECT

For short intervals when an elevator is traveling away from the fire floor, piston effect reduces the pressure difference from the elevator lobby to the rest of the building. In extreme cases this could result in smoke infiltration into the elevator lobby.

The following analysis is intended to provide an understanding of piston effect and its effect on the pressure difference from the elevator lobby to the building. Also, the analysis may be useful in evaluating smoke movement in buildings when elevators are used for fire fighting and for rescue. For the sake of simplicity, buoyancy, wind, stack effect, and the **HVAC** system have been omitted from this analysis. Omitting stack effect is equivalent to stipulating that the building air temperature is equal to the outside air temperature.

**A** downward-moving elevator car forces air out of the section of shaft below the car and into the section of shaft above the car as illustrated in Fig. 1. The law of conservation

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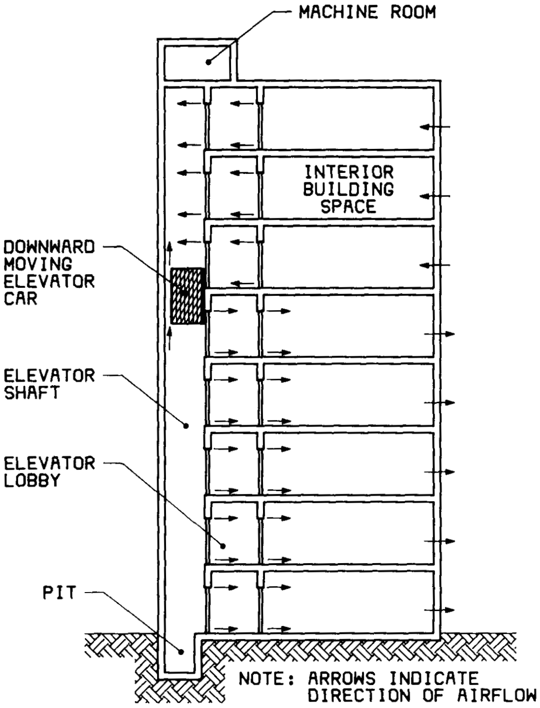


Fig. 1. Airflow due to downward movement of elevator car.

of mass can be written for the volume, $Q_a$, above the car

$$\begin{pmatrix}\text{Net mass flow}\\ \text{(into a volume, } Q_a\text{)}\end{pmatrix} = \begin{pmatrix}\text{Rate of mass change}\\ \text{within volume, } Q_a\end{pmatrix}$$

$$\dot{m}_{oa} + \dot{m}_{ba} = \frac{d}{dt}(\rho Q_a) \tag{1}$$

where

$\dot{m}_{oa}$ = mass flow rate from outside to volume, Qa

$\dot{m}_{ba}$ = mass flow rate from below the elevator car, $Q_b$, to volume, $Q_a$

$\rho$ = air density within shaft.

The volumes $Q_a$ and $Q_b$ are changing as the elevator car descends. For a downward elevator car velocity, $V$, and a cross-sectional area of the shaft, A,, the derivative of the volume, $Q_a$, can be expressed as

$$\frac{dQ_a}{dt} = A_s V \tag{2}$$

The air density is essentially constant within the shaft. Therefore, substituting eqn. (2) into eqn. (1) yields

$$\dot{m}_{oa} + \dot{m}_{ba} = \rho A_s V \tag{1a}$$

Modern elevators operate at various speeds up to a maximum of 2000 fpm (10 $\text{ms}^{-1}$). Strakosch [3] discusses elevator velocity and acceleration. In most cases an elevator will accelerate such that within a distance of one floor the car will be near or at its rated speed. Because acceleration time is relatively short and its influence on piston effect is minor if any at all, acceleration is eliminated from this analysis.

To expedite the analysis, the flow areas are chosen such that they are the same for each floor of the building and that the only vertical airflow in the building is within the elevator shaft. The mass flow rate from the outside to Q, is

$$\dot{m}_{oa} = N_a C A_e \sqrt{2\rho(P_o - P_a)} \tag{3}$$

where

$N_a$ = number of floors above the car
$C$ = flow coefficient
$A_e$ = effective flow area per floor between the shaft and the outside
$P_o$ = outside air pressure
$P_a$ = shaft air pressure above the car.

Pressure difference due to elevation (hydrostatic pressure) has been eliminated from eqn. (3) because there is no indoor-to-outdoor temperature difference. The effective flow area of a system of flow paths is the area that results in the same flow as the system when subjected to the same pressure difference. The ASHRAE smoke control manual [4] presents a detailed discussion of effective flow areas.

For the space below the car, the mass flow rate from $Q_b$ to the outside is

$$\dot{m}_{bo} = N_b C A_e \sqrt{2\rho(P_b - P_o)} \tag{4}$$

where

$N_b$ = number of floors below the car
$P_b$ = shaft air pressure below the car.

Because the absolute pressure in the shaft is nearly constant, the flow rate entering the shaft can be considered equal to the flow rate of mass leaving the shaft. Thus, equating the right-hand sides of eqns. (3) and (4), cancelling like terms and rearranging yields

$$\frac{P_b - P_o}{P_o - P_a} = (N_a/N_b)^2 \tag{5}$$

The pressure drop from the bottom to the top of a moving elevator car is accounted for by disturbances in the flow caused by obstructions such as the car edges and protrusions from the car and by friction. Again, neglecting hydrostatic pressure difference, the mass flow rate from below the car to above it can be expressed as

$$\dot{m}_{\mathrm{ba}} = A_{\mathrm{f}} C_{\mathrm{c}} \sqrt{2\rho(P_{\mathrm{b}} - P_{\mathrm{a}})} \qquad (6)$$

where

$A_{\mathrm{f}}$ = free flow area in the shaft around the car or cross-sectional area of the shaft less the cross-sectional area of the car

$C_{\mathrm{c}}$ = flow coefficient for flow around the car.

To evaluate the flow coefficient, $C_{\mathrm{c}}$, tests were run on a twelve-story, two-car elevator shaft at the NBS administration building. A discussion of these tests is provided in the Appendix. For one car traveling in the two-car shaft the flow coefficient was 0.94, and for two cars traveling side-by-side together the flow coefficient was 0.83. The case with the two cars moving together was tested to obtain an approximation of a car moving in a single car shaft.

Combining eqns. (1a), (3), (5) and (6) yields

$$P_{\mathrm{o}} - P_{\mathrm{a}} = \frac{\rho}{2}\left[\frac{A_{\mathrm{s}} V}{N_{\mathrm{a}} C A_{\mathrm{e}} + C_{\mathrm{c}} A_{\mathrm{f}} \sqrt{1 + (N_{\mathrm{a}}/N_{\mathrm{b}})^2}}\right]^2 \qquad (7)$$

For the flow paths illustrated in Fig. 1, the effective flow area per floor of the three paths in series from the shaft to the outside is

$$A_{\mathrm{e}} = \left[\frac{1}{A_{\mathrm{sl}}^2} + \frac{1}{A_{\mathrm{li}}^2} + \frac{1}{A_{\mathrm{io}}^2}\right]^{-1/2} \qquad (8)$$

where

$A_{\mathrm{sl}}$ = leakage area between the shaft and the elevator lobby

$A_{\mathrm{li}}$ = leakage area between the elevator lobby and the building

$A_{\mathrm{io}}$ = leakage area between the building and the outside.

For paths in series the pressure difference across one of the paths equals the pressure difference across the system times the square of the ratio of effective area of the system to the flow area of the path in question. Thus, for flows above the elevator car, the pressure difference, $\Delta P_{\mathrm{li}}$, between the lobby and the building is

$$\Delta P_{\mathrm{li}} = (P_{\mathrm{o}} - P_{\mathrm{a}})(A_{\mathrm{e}}/A_{\mathrm{li}})^2 \qquad (9)$$

Substituting eqn. (7) into this yields

$$\Delta P_{\mathrm{li}} = \frac{\rho}{2}\left[\frac{A_{\mathrm{s}} V (A_{\mathrm{e}}/A_{\mathrm{li}})}{N_{\mathrm{a}} C A_{\mathrm{e}} + C_{\mathrm{c}} A_{\mathrm{f}} \sqrt{1 + (N_{\mathrm{a}}/N_{\mathrm{b}})^2}}\right]^2 \qquad (10)$$

This relation expresses the pressure difference, $\Delta P_{\mathrm{li}}$, produced above a downward-moving car as a function of the car velocity, the building flow paths and the position of the car.

## PISTON EFFECT EXPERIMENT

To test this calculation, experiments were conducted on an elevator in a hotel in Toronto, Ontario, Canada. The elevator shaft was 15 stories tall with a height between floors of 8.53 ft (2.60 m). The flow areas and car velocity are listed in Table 1. Flow areas $A_{\mathrm{sl}}$, $A_{\mathrm{li}}$, and $A_{\mathrm{io}}$ were determined by pressurization tests. The areas $A_{\mathrm{s}}$ and $A_{\mathrm{f}}$ were evaluated by the same method as was used in the Appendix. The car velocity was based on the heights between floors. The effects of wind, buoyancy, stack effect and the HVAC system were not significant during these tests. The techniques of the experiments are those that have been used for many pressurization tests conducted by the NRCC [5 - 8].

**TABLE 1**

**Experimentally determined data for an elevator in a hotel in Toronto, Ontario, Canada**

| | | |
|---|---|---|
| $A_{\mathrm{sl}}$, area between shaft and lobby | 1.41 ft$^2$ | 0.131 m$^2$ |
| $A_{\mathrm{li}}$, area between lobby and building | 0.97 ft$^2$ | 0.0901 m$^2$ |
| $A_{\mathrm{io}}$, area between building and outside | 4.85 ft$^2$ | 0.450 m$^2$ |
| $A_{\mathrm{s}}$, cross-sectional area of shaft | 59.37 ft$^2$ | 5.515 m$^2$ |
| $A_{\mathrm{f}}$, free area of shaft | 20.96 ft$^2$ | 1.947 m$^2$ |
| $V$, velocity of elevator car | 341 fpm | 1.73 m/s |

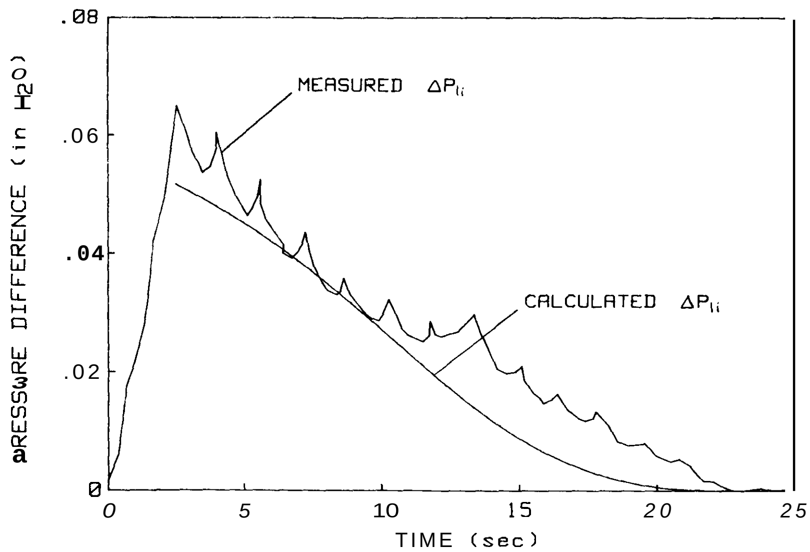


**Fig. 2. Pressure difference, $\Delta P_{li}$, across the elevator lobby of a Toronto hotel** due **to piston effect. Conversion factor: 1** in **$H_2O$ = 248.8 Pa.**

The measured pressure difference, $\Delta P_{li}$, for the elevator car descending from the top floor is shown on Fig. 2. The pressure difference was measured at the floor level of the top floor, and the pressure peak occurs as the top of the car passes the differential pressure transducer. With the exception of some pulsations the $\Delta P_{li}$ decreases as the car descends. Also Fig. 2 shows $\Delta P_{li}$ calculated from eqn. (10) using the measured data from Table 1. The calculations are in good agreement with the measurements. The measured pulsations are believed to be the result of effective change in shaft size as the car passes the housing for the automatic doors.

**MAXIMUM VALUE OF $\Delta P_{li}$**

Examination of eqn. (10) shows that $\Delta P_{li}$ cannot exceed the limits of

$$(\Delta P_{li})_u = \frac{\rho}{2}\left[\frac{A_s A_e V}{A_f A_{li} C_c}\right]^2 \qquad (11)$$

where the subscript u denotes the upper limit.

This relation assumes that the elevator piston effect is the only driving force of air movement in the building and that vertical flow can only exist in the elevator shaft. This relation is for elevator shafts which are unvented or for which the vents are closed. Equation **(11)** was derived for a pressure difference $\Delta P_{li}$, on floors above the car for a descending car, however it is also valid for floors below an ascending car. Equation **(11)** can be used to estimate the magnitude of pressure difference across the elevator lobby due to piston effect.

The pressure difference, $(\Delta P_{li})_u$, is strongly dependent upon V, **A,** and $A_f$. For example, Fig. **3** shows the calculated relationship between $(\Delta P_{li})_u$ and **V** due to one car moving in a single car shaft, a double car shaft and a quadruple car shaft based on the flow areas listed in Table **2.** These flow areas are based on the measured values of ***A***, from the tests in the NBS administration building reported in the Appendix and average values from Appendix C of the ASHRAE smoke control manual for a building with a floor size of 46.0 ft X 222 ft (14.0 m X 67.7 m) and 10.17 ft **(3.099** m) between floors. Leakage values for walls and floors listed in the ASHRAE smoke control manual are based on measurements by the National Research Council of Canada [5 - 8].

As expected the $(\Delta P_{li})_u$ is much greater in the case of the single shaft. It seems a safe recommeridation that single car shafts should not be used for fire evacuation except when car velocities are very low. Freight elevators are of concern because they are often in single car shafts. In the above example, the same shaft dimensions were used for all the car velocities for the purpose of comparison.

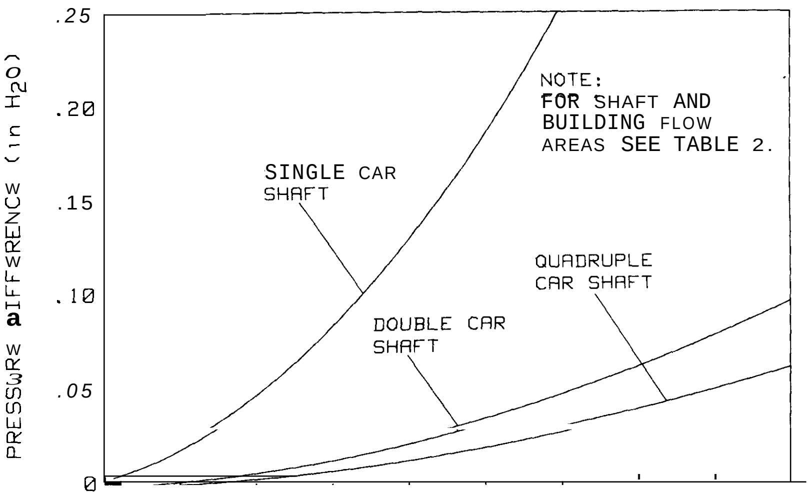


Fig. 3. Example pressure differences from building to elevator lobby due to piston effect. Conversion factors: 1 in $H_2O$ = 248.8 Pa; 1 fpm = 0.00508 $ms^{-1}$.

TABLE 2

Flow areas for elevator piston-effect analysis*

| | $ft^2$ | $m^2$ |
|---|---|---|
| $A_{sl}$, area between shaft and lobby | 1.60 | 0.149 |
| $A_{li}$, area between lobby and building | 0.42 | 0.0390 |
| $A_{io}$, area between building and outside | 0.54 | 0.0502 |
| ***For single car shaft*** | | |
| $A_s$, cross-sectional area of shaft | 60.4 | 5.61 |
| $A_f$, free flow area around car | 19.4 | 1.80 |
| ***For double car shaft*** | | |
| $A_s$, cross-sectional area of shaft | 120.8 | 11.22 |
| $A_f$, free flow area around car | 79.8 | 7.41 |
| ***For quadruple car shaft*** | | |
| $A_s$, cross-sectional area of shaft | 241.5 | 22.44 |
| $A_f$, free flow area around car | 200.5 | 18.63 |

*For a single car shaft a value of $C_c$ = 0.83 was used. For double and quadruple car shafts a value of $C_c$ = 0.94 was used.

Minimum shaft dimensions for electric, hydraulic, hospital and observation elevators are listed by the National Elevator Industry, Incorporated [9]. An analysis of piston-effect-induced pressure differences during elevator shaft pressurization is planned for a future paper.

## CONCLUSIONS

The piston effect analysis was in very good agreement with the measurements from the Toronto hotel experiment. Piston effect is not a concern for slow-moving elevator cars in multiple car shafts. However, for fast cars in single car shafts, the piston effect can be considerable. Equation (11) can be used to evaluate the magnitude of pressure differences produced by piston effect for specific applications.

## LIST OF SYMBOLS

| | |
|---|---|
| *A* | area |
| C | flow coefficient |

| | |
|---|---|
| $m$ | mass flow rate |
| $N$ | number of floors |
| $P$ | pressure |
| $\Delta P$ | pressure difference |
| $Q$ | volume |
| $t$ | time |
| $V$ | elevator car velocity |
| $\rho$ | density |

*Subscripts*

| | |
|---|---|
| a | above elevator car |
| b | below elevator car |
| o | outside |
| s | shaft |
| e | effective |
| f | free flow around car |
| 1 | elevator lobby |
| i | building |
| u | upper limit |

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APPENDIX

*Evaluation of elevator car flow coefficient*

In order to determine the flow coefficient for flow around an elevator car, tests were performed on a twelve-story, two-car elevator shaft at the NBS administration building. The test concept was to eliminate leakage from the elevator shaft so that the flow across the elevator cab would be

$$\dot{m}_{ba} = \rho A_s V \tag{A1}$$

The mass flow pressure relation across the car is given by eqn. **(6)**

$$\dot{m}_{ba} = A_f C_c \sqrt{2\rho(P_b - P_a)} \tag{6}$$

Combining eqns. **(A1)** and (6) and solving for the flow coefficients

$$C_c = \frac{A_s V}{A_f \sqrt{\frac{2}{\rho}(P_b - P_a)}} \tag{A2}$$

This relation is for a downward-moving car, however a similar relation can be developed for an upward-moving car.

The elevator tests had the mechanical room located above the shaft with holes in the shaft for the cables and vents. Because the cable could not be sealed during tests, both the shaft and mechanical room were sealed by taping over all cracks and gaps around doors and blocking off all vents to the outside. The areas, $A_s$ and $A_f$, were calculated according to the convention illustrated in Fig. **A1.**

Because of difficulties in changing the car velocity, tests were limited to two car velocities, and data from these tests are listed in

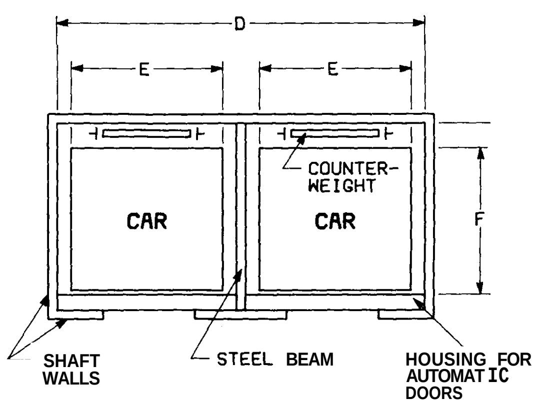


Fig. A1. Convention used for determination of $A_s$ and $A_f$. $A_s = DG$ and $A_f = DG - NEF$ where $N$ = **1** for a single car moving and $N$ = **2** for both cars moving together. Note that the area, $A_f$, does not include the small area between the car and the door housing because it is felt that the contribution of this area is insignificant.

TABLE A1

Data and results from car flow coefficient tests

| Shaft temperature | 76 °F | 24 °C |
|---|---|---|
| *Tests with 1 car moving* | | |
| $A_s$ | 120.8 ft$^2$ | 11.22 m$^2$ |
| $A_f$ | 79.8 ft$^2$ | 7.41 m$^2$ |
| $P_b - P_a$ at V = 496 fpm (2.52 m/s) | 0.039 in $H_2O$ | 9.8 Pa |
| $P_b - P_a$ at V = 330 fpm (1.68 m/s) | 0.016 in H20 | 4.0 Pa |
| $C_c$ | 0.94 | 0.94 |
| *Tests with 2 cars moving together* | | |
| $A_s$ | 120.8 ft$^2$ | 11.22 m$^2$ |
| $A_f$ | 38.8 ft$^2$ | 3.60 m$^2$ |
| $P_b - P_a$ at V = 496 fpm (2.52 m/s) | 0.21 in $H_2O$ | 53 Pa |
| $P_b - P_a$ at V = 330 fpm (1.68 m/s) | 0.076 in $H_2O$ | 19 Pa |
| $C_c$ | 0.83 | **0.83** |

Table **A1.** Tests were performed with both cars moving together. This was done in an attempt to simulate the effect of a single car moving in a single car shaft.

The flow coefficients listed in Table A1 were calculated from the greater car speed because the higher speeds are of greater concern in regard to piston effect. However, the flow coefficients calculated at the lower speed differ only by 4% for a single car moving and by 10% for two cars moving together. This tends to support the treatment in the paper of the flow coefficient as being constant with respect to velocity.