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PRESSURE DROP CHARACTERISTICS OF TYPICAL STAIRSHAFTS IN HIGH-RISE BUILDINGS

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ABSTRACT

Little information exists on the pressure drop characteristics in tall buildings. Full-scale tests were conducted, therefore, to develop data on the airflow resistance required for designing a smoke control system for stairshafts by the pressurization technique. Data were obtained for open and closed tread stairshafts, with and without people inside them. The study revealed that the flow resistance inside the stairshaft with people can be double that without people. Also, a simple physical model to simulate the effect of people on the flow resistance was developed. This paper describes the analytical model, the experimental study, and the data obtained on the airflow resistance for the various stair configurations.

INTRODUCTION

Smoke spreads rapidly from the fire region to other areas in the building through leakage openings in the floor construction and vertical shafts. The stairwells are the principal means of escape from a building and should be protected effectively to permit safe evacuation during a fire. One concept often used for protecting the stairwells is the pressurization technique, which involves increasing the pressure inside the shaft above those of immediately surrounding floor spaces by injecting outdoor air with a supply fan. A knowledge of the airflow resistance inside the stairwell, which has a significant impact on the pressure distribution, is required for analysis of the airflow network and prediction of smoke movement by computer models.

The data on airflow resistance available in the literature (Cresci 1973; Tamura 1974; Shaw 1976; Marshall 1985) do not consider the effect of various stair configurations, floor heights and, more significantly, the effect of people on the pressure loss, which could seriously affect the performance of a pressurization system. In this study, these factors were investigated and new data on airflow resistance have been developed.

ANALYTICAL MODEL

In the model for airflow and pressure inside a stairwell (Figure 1), it is assumed that all leakage openings in the walls of the shaft can be represented by an orifice located in the shaft wall at mid-height of each floor. The pressure difference between the ith and i+1th floors is

$$P_{s,i} - P_{s,i+1} = \rho_i g h_i + 2\left[\frac{\rho_i}{2}\left(\frac{Q_{s,i}}{A_s}\right)^2 - \frac{\rho_{i+1}}{2}\left(\frac{Q_{s,i+1}}{A_s}\right)^2\right] + K\frac{h_i}{D_e}\frac{\rho_i}{2}\left(\frac{Q_{s,i}}{A_s}\right)^2 \qquad (1)$$

The first, second, and third terms on the right side of Equation 1 represent pressure differences due to column weight of air, momentum pressure loss due to air leakage, and frictional pressure loss (based on Darcy's equation for air ducts), respectively. The mass flow rate at the level of the ith floor is

$$\rho_i Q_{s,i} = \rho_i Q_{s,i-1} - \rho_i Q_{\ell,i} \qquad (2)$$

where the leakage flow is

$$\rho_i Q_{\ell,i} = CA_{\ell,i}\,[2\rho_i(P_{s,i} - P_{f,i})]^{1/2} \qquad (3)$$

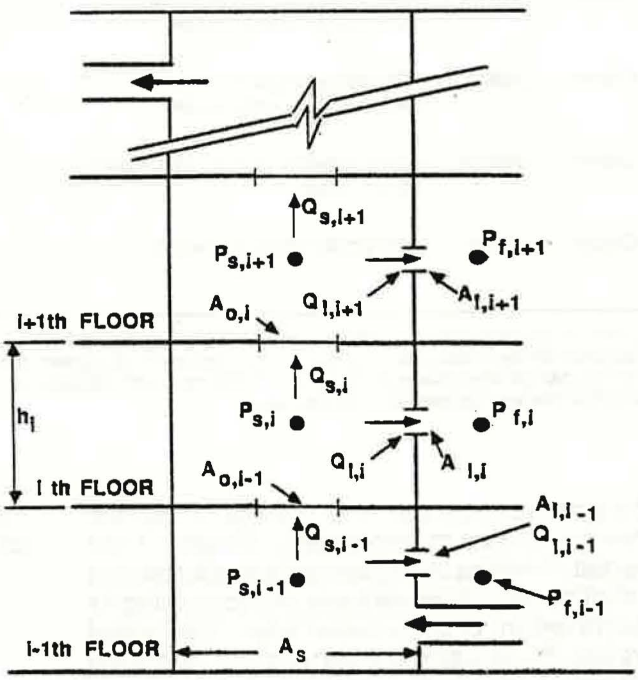

Figure 1 *Stairshaft model for pressures and airflows*

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TABLE 1
Pressure Drop Characteristics of Test Stairwell, Floor Height: 2.6 m (8.5 ft)

Test No.	Stair Treads	Supply air injection	Stairwell occupancy conditions	Flow rate m^3/s (cfm)	Press. drop per floor, Pa (in of water)	Press. loss coefficient K	A_o/A_s per floor*
1	Open	Bottom	No occupants	10 (21,200) 7.5 (15,900) 5 (10,600)	18.3 (0.073) 10.5 (0.042) 4.7 (0.019)	61 62 63	0.24 0.24 0.24
2	Open	Bottom	With simulation at high density,** using models	10 (21,200) 7.5 (15,900) 5 (10,600)	32 (0.128) 17.5 (0.070) 8 (0.032)	107 104 107	0.18 0.18 0.18
3	Open	Top	No occupants	10 (21,200) 7.5 (15,900) 5 (10,600)	18 (0.072) 10 (0.040) 4.5 (0.018)	60 59 60	0.24 0.24 0.24
4	Open	Top	With simulation (as in Test 2)	10 (21,200) 7.5 (15,900) 5 (10,600)	30 (0.120) 17 (0.068) 7.7 (0.031)	101 101 103	0.19 0.19 0.19
5	Closed	Bottom	No occupants	10 (21,200) 7.5 (15,900) 5 (10,600)	20.2 (0.081) 11.4 (0.046) 5 (0.020)	67 68 67	0.23 0.23 0.23
6	Closed	Bottom	With simulation (as in Test 2)	10 (21,200) 7.5 (15,900) 5 (10,600)	52.5 (0.211) 28 (0.112) 13 (0.052)	175 166 174	0.14 0.15 0.14
7	Closed	Top	No occupants	10 (21,200) 7.5 (15,900) 5 (10,600)	22.6 (0.091) 13 (0.052) 5.5 (0.022)	75 77 73	0.22 0.21 0.22
8.1	Closed	Bottom	With people: at high density,** on 2 adj. floors	10 (21,200) 7.5 (15,900) 5 (10,600)	N/A 33.5 (0.135) 13.5 (0.054)	N/A 199 180	N/A 0.13 0.14
8.2	Closed	Bottom	With people: at medium density,*** on 2 adj. floors	10 (21,200) 7.5 (15,900) 5 (10,600)	N/A 22.5 (0.090) 9.5 (0.038)	N/A 133 127	N/A 0.16 0.17
9.1	Closed	Bottom	With simulation: at high density,** (as in test 8.1) using models	10 (21,200) 7.5 (15,900) 5 (10,600)	50 (0.200) 29 (0.116) 12.5 (0.050)	167 172 167	0.15 0.14 0.15
9.2	Closed	Bottom	With simulation: at medium density,*** (as in test 8.2) using models	10 (21,200) 7.5 (15,900) 5 (10,600)	36.5 (0.146) 21.2 (0.085) 9.2 (0.037)	122 127 123	0.17 0.17 0.17
10	Closed	Bottom	With simulation: at medium density,*** on adj. floors	10 (21,200) 7.5 (15,900) 5 (10,600)	N/A 19.7 (0.079) 8.8 (0.035)	N/A 117 117	N/A 0.17 0.17
11	Closed	Bottom	With simulation: as per test 10	10 (21,200) 7.5 (15,900) 5 (10,600)	35.2 (0.141) 19.6 (0.079) 8.8 (0.035)	117 116 117	0.17 0.17 0.17

* A_o/A_s per floor: is the flow resistance in terms of equivalent orifice area to shaft area.
** High occupant density: is based on 2.0 persons/m^2 (0.18 person/ft^2), (33 persons between 2 floors).
*** Medium occupant density: is based on 1.0 person/m^2 (0.09 person/ft^2), (18 persons between 2 floors).
N/A Indicates that data were not obtained at that flow rate.

If the shaft is sealed, with no air leakage through the walls, then the momentum change term in Equation 1 can be neglected. Therefore, by measuring the pressures in the sealed shaft for two successive floors and accounting for the column weight of air between them, the friction pressure loss, $P_{f(i)}$, can be measured and the value of the pressure loss coefficient, K, can be calculated:

$$K = \frac{\Delta P_{f(i)}}{\frac{h_i}{D_e}\frac{\rho_i}{2}\left[\frac{Q_{s,i}}{A_s}\right]^2} \quad (4)$$

For the purpose of computer modeling of building airflow network and smoke concentrations during a fire, $P_{f(i)}$ can be represented by a pressure loss across an orifice located between floors of a frictionless shaft.

$$\Delta P_{f(i)} = \frac{1}{C_d^2}\frac{\rho_i}{2}\left[\frac{Q_{s,i}}{A_{o,i}}\right]^2 \quad (5)$$

For design purposes, the flow resistance can be represented by a ratio of the equivalent orifice area to shaft area, A_o/A_s. From Equations 4 and 5:

$$\frac{A_o}{A_s} = \frac{1}{C_d\ (K\ h/D_e)^{1/2}} \quad (6)$$

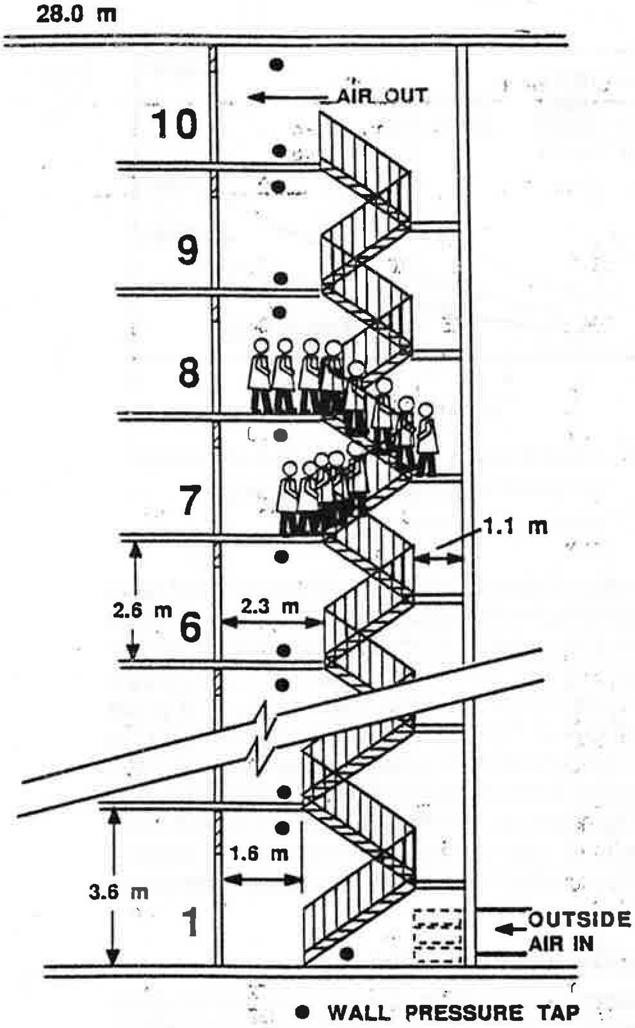


Figure 2 *Experimental stairshaft: location of pressure taps and occupant distribution*

EXPERIMENTAL DETAILS

The tests were conducted to establish the value of K for various stair configurations so that values of A_o in Equation 6 can be determined and applied to computer models for investigating the performance of various pressurization systems. The full-scale experiments were designed to investigate major factors influencing the flow resistance, including open and closed tread, floor heights of 2.6 m and 3.6 m (8.5 ft and 12 ft), with and without people in the stairs, and with pressurization by either bottom or top injection.

Test Facility

All tests were conducted in the stairwell of the 10-story experimental fire tower at the National Fire Laboratory of the National Research Council of Canada. The stairwell (Figure 2) is a conventional type with open-tread metal stairs that can be modified to closed-tread configuration. The shaft has a cross-sectional area of 12.5 m^2 (134 ft^2) and a total height of 28 m (92 ft); the first and second floors are 3.6 m (12.0 ft) high and the remainder are 2.6 m (8.5 ft) high. The stairway slope and stair treads are identical for all floors. A detailed description of the test facility, including airflow monitoring systems, instrumentation, calibration, and measuring techniques, is given in Achakji (1987).

TABLE 2
Flow Resistance of Conventional Stairwell, Typical Floor Height: 3.6 m (12 ft)

Test No.	Stairwell Configuration	Pressure loss Coefficient (K)	A_o/A_s per floor
1	Open-tread metal stairs with no occupants inside the shaft	29	0.30
2	Closed-treads metal stairs with no occupants inside the shaft	32	0.28

Note: The values in this table are the average data of bottom and top air injections at different flow rates of 5 to 10 m^3/s (10,600 to 21,200 cfm).

Test Method

The effect of the air leakage flow on the pressure gradient inside the shaft was minimized and made insignificant by sealing all openings and leakage cracks of the shaft, including all stair doors. With bottom injection, outdoor air was supplied at the bottom and allowed to flow up and out through the open stair door and open outside wall vents at the top floor. With top injection, air was supplied at the top and allowed to flow down and out through the open exit door at the bottom. Various flow rates were used for each configuration ranging from 5 to 10 m^3/s (10,600 to 21,200 cfm) (0.9×10^5 Re 1.8×10^5). The test program is summarized in Tables 1 and 2.

The pressure differences between floors inside the stairwell were measured using a total of 20 pressure taps (two for each floor), which were located as shown in Figure 2 and connected to two pressure switch units located on the ground floor; each unit is connected to a pressure transducer whose outputs were recorded on a chart recorder. The airflow rates were measured using a calibrated air-monitoring system.

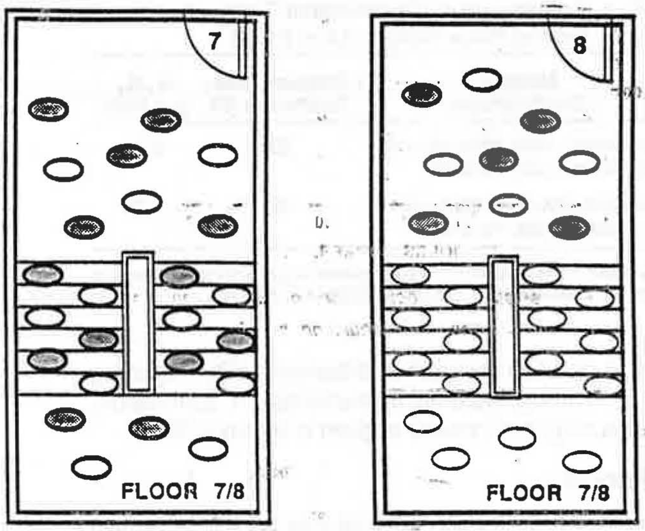
Simulation of Occupants and Evacuation Condition

An ideal approach to investigate the airflow resistance during evacuation is by testing with a large number of people inside the stairshaft. If not possible, a simple physical model based on the volume of a human body can be used. The model used was made of a cylindrical tube (commercially available), 0.31 m (1.0 ft) O.D. and 1.8 m (5.9 ft) high, to give the frontal area and height, respectively, of an average-sized adult.

The evacuation of people was simulated by placing a given number of either people or tubes on and between floors 7 and 8 (Figure 2). From the limited data for high-density crowd movement down stairs during evacuation, the values of 2.0 and 1.0 person/m^2 (0.18 and 0.09 person/ft^2) were assumed for high and medium density, respectively (Pauls and Jones 1980). The location and distribution of people are shown in Figure 3.

RESULTS AND DISCUSSION

The results are summarized in Tables 1 and 2 for floor heights of 2.6 m and 3.6 m (8.5 ft and 12.0 ft), respectively. The internal flow resistance is expressed as a pressure loss



NOTES:
- HIGH OCCUPANT DENSITY INCLUDES ALL POSITIONS SHOWN
- MEDIUM OCCUPANT DENSITY INCLUDES ONLY THE DARK POSITIONS

Figure 3 *Location of occupants inside the stairshaft for high and medium occupant densities*

coefficient (K) and the ratio of equivalent orifice area to stairwell cross-sectional area (A_o/A_s) for various stair configurations and evacuation conditions. The pressure drop values between two adjacent floors are also presented in Table 1 with their corresponding airflow rates.

Effects of Open and Closed Stair Treads

Table 1 shows that the top and bottom air injections have similar pressure drop characteristics for both the open- and closed-tread stairs. Pressure drop profiles in Figure 4 show a marked change in slope at 7.2 m (24 ft) separating the two pressure drop zones; the first represents the pressure drops of the first and second floors and the second represents those of the remaining floors. The larger pressure drop for the second zone is mainly due to the larger landing area of this zone, which causes greater obstruction to the air flow in the horizontal plane. The results indicate that, at a given airflow rate, the pressure loss varies linearly with the height of the stairwell.

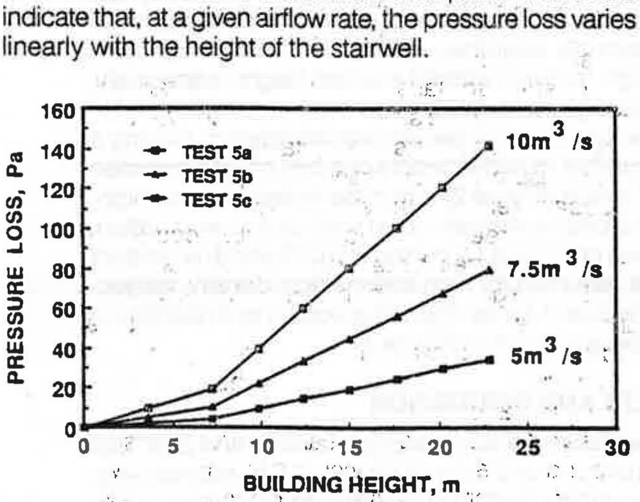


Figure 4 *Pressure drop distribution: with or without occupant simulation (closed treads, bottom injection)*

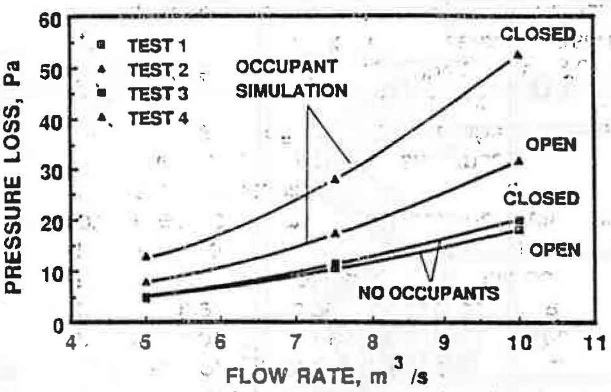


Figure 5 *Pressure drop between floors 7 and 8: effect of open and closed treads, with and without occupant simulation, bottom injection*

The results (Table 1) indicate that the open-tread stairs present less resistance to flow than the closed-tread stairs due to the additional flow passages provided between treads for the former. The effects of open and closed treads become more significant when there are people in the stairs. As shown in Figure 5, without occupants inside the stairs, the differences in the pressure drop between open and closed tread are within 8%. With occupants inside the shaft (at high density), the resistance of the closed tread was increased significantly over that of open tread—by 62%. These effects are further discussed in the following section.

Effects of Occupants in Stairs

This effect was investigated using a physical model to simulate people. The tests with people were also performed, but only for the closed tread stair configuration.

Model Effect. The pressure drop distributions inside the shaft with and without simulated occupants (floors 7 and 8) are shown in Figure 6 for the closed-tread stairs. At an airflow rate of 10 m³/s (22,000 cfm), as shown in Figure 5, the pressure drops between floors 7 and 8

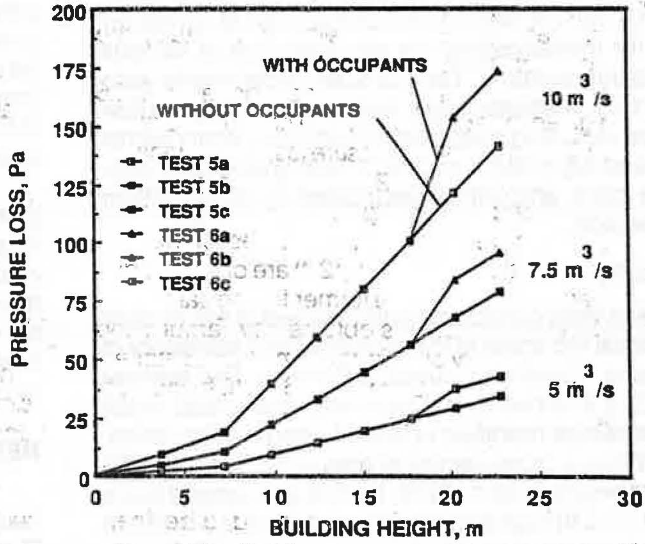


Figure 6 *Pressure drop distribution: with or without occupant simulation (closed treads, bottom injection)*

without occupants are 18 and 20 Pa (0.07 and 0.08 in of water) for the open-and-closed-tread stairs, respectively. These values are increased with occupants inside the shaft to 32 and 52.5 Pa (0.13 and 0.21 in of water), respectively. This effect was duplicated with other airflow rates. In terms of flow resistance (Figure 7), the average values of the coefficient K with no occupants are 62 for the open tread and 67 for the closed tread. These coefficients are increased significantly with simulated occupants at high density to 103 for the open-tread stairs and 163 for the closed-tread stairs. Correspondingly, the overall equivalent orifice area without occupants for both open and closed tread is about 23% of the shaft cross-sectional area; with occupants at high density, this value is decreased to 18% for the open-tread stairs and 14.5% for the closed-tread stairs.

People Effect. Tests 8.1 and 8.2 were conducted with real people at high and medium occupant densities. The results indicated a significant increase in the pressure drop similar to those of the physical model. With people at high density, the pressure drop increased by factors of 3.0 and 2.5 at medium and low airflow rates, respectively; at medium density, they were 2.0 and 1.9. The data clearly indicate that K depends on occupant density (Figure 8).

Validation of the Simulation Method. To validate the simulation method used, tests 9.1 and 9.2 were conducted with the models placed in the same locations as in the tests with people. The results in Figure 9 indicate a good agreement with those obtained with people; in terms of K, the simulation method is within 4% for medium occupant density and 11% for high occupant density. Tests 10 and 11 were conducted using the same number of occupants for high density but distributed on three floors (6, 7, and 8) instead of two to represent a medium occupant density on each of these floors. As expected, the results were approximately the same for both configurations, i.e., occupants on two and on three floors with medium occupant density.

Effect of Floor Heights

In tall buildings, the floor height varies from one building to another; generally it is between 2.6 m and 3.6 m (8.5 ft and 12 ft). However, in a typical stairwell, the cross-sectional area of the shaft and the stairway slope, rise/step, are usually constant regardless of height. In this study, the two bounding heights were investigated.

The pressure loss coefficients for the floor height of 2.6 m (8.5 ft) are given in Table 1 and those of 3.6 m (12 ft) are given in Table 2. The average pressure loss coefficients, K, for the closed-tread stairs are 32 and 67 and for the open-tread stairs are 29 and 62 for heights of 3.6 m and 2.6 m (12 ft and 8.5 ft), respectively. The larger K values for the floor height of 2.6 m (8.5 ft) than of 3.6 m (12 ft) are probably due to the larger landing area for the former for the same stair slope. Field test measurements obtained by Tamura and Shaw (1976) in multi-story buildings (from 11 to 28 stories) with floor heights between 3.04 m and 3.6 m (10 ft and 12 ft) indicate that the average value of K was 35.

CONCLUSIONS

1. The friction pressure drop was found to be linear with height and varied directly with the square of the supply air rates. The pressure loss coefficient, K, was independent of the Reynolds number for the range of flow rates used for stairwell pressurization.

2. The open-tread stairs presented less resistance to flow than the closed-tread stairs; this difference was more pronounced with occupants on the stairs.

3. The pressure loss coefficients were greatly affected by the occupant density in the stairwell; at high occupant density, about three times and at medium occupant density, about two times those without occupants.

4. For floor heights of 2.6 m and 3.6 m (8.5 ft and 12 ft), which affect the area of landings for stairs with the same slope and cross-sectional area of shaft, the pressure loss coefficient of the former was twice that of the latter.

5. The simulation method using simple physical models was verified by tests with real people. The results indicated good agreement; the accuracy in terms of K was within 4% and 11% for medium and high occupant densi-

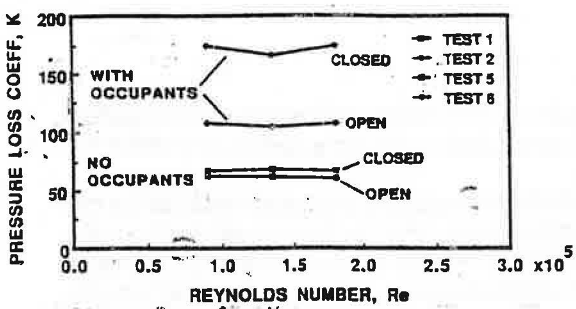


Figure 7 *Flow resistance: effect of open and closed treads, with and without occupant simulation (bottom injection)*

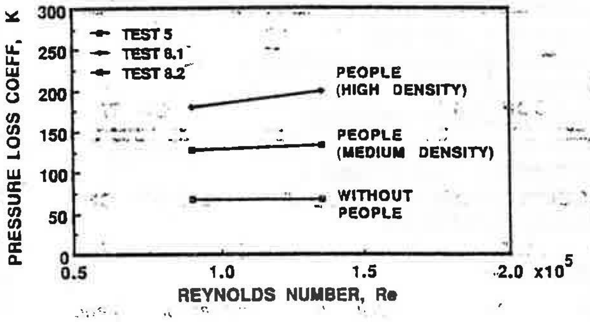


Figure 8 *Flow resistance: effect of people at high and medium occupant densities (closed treads, bottom injection)*

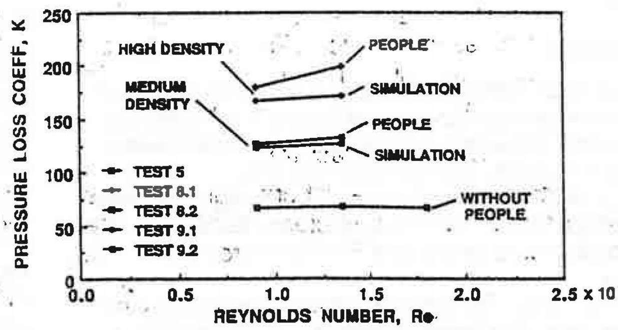


Figure 9 *Validation of the simulation method by comparison with people tests (closed treads, bottom injection)*

ties, respectively. This method can be used in future testing of stairwell pressurization systems, particularly under fire conditions.

6. The tests involved single injection, either at the top or bottom of the stairwell. Further tests are required to investigate the effect of multiple air injections on the pressure distribution inside stairwells with and without occupants.

NOMENCLATURE

- A = cross-sectional area, m^2 (ft^2)
- C_d = coefficient of discharge (0.6 for turbulent flow)
- D_e = equivalent diameter, m (ft); $D_e = [4 A_s/p]$, where p = perimeter of the shaft
- g = acceleration due to gravity, m/s^2 (ft/s^2)
- h = height of floor, m (ft)
- K = friction pressure loss coefficient
- N = number of floors served by the stairwell in a building
- P = static pressure, Pa (in of water)
- Q = volumetric flow rate, m^3/s (cfm)
- ρ = air density, kg/m^3 (lb/ft^3)

Subscripts

- f = floor
- i = location (ith floor)
- l = ground floor
- ℓ = leakage
- s = shaft

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DISCUSSION

R. Pitzer, Jim Grigsby, P.E., Corpus Christi, TX: In response to the problems of door leakage, our experience has shown door leakage and general construction materials and practices can be significant. A 10-story residential building with exterior stairwells had two propeller fans (one in the basement and one on the fifth floor) with relief at the roof. The initial pressurization test produced readings of 0.02 in W.C. Weatherstripping the doors and caulking conduit and similar penetrations yielded readings of 0.06 in W.C., still falling short of the required 0.15 in W.C. Two coats of latex paint on the cinderblock walls resulted in final test pressures of 0.18 in W.C.

G.Y. Achakji: The designers of pressurization systems must account for the air leakage in the shaft before sizing the capacities of the fans. Some shafts produce more leakage than others, depending on the quality of workmanship and the construction materials used. An air leakage test can be conducted to check that. Much information exists on air leakage; data are available in the literature (Tamura and Shaw 1976).

I must point out, however, that the emphasis in this paper is on determining the effect of various stair configurations and floor heights and the effect of occupants on the pressure loss, which were not known or available before.