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AIR LEAKAGE DATA FOR THE DESIGN OF ELEVATOR AND STAIR SHAFT PRESSURIZATION SYSTEMS

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SOMMAIRE

Un éventail de 50,000 pi^3/mn (23.5-m^3/s) monté sur une remorque a été utilisé pour déterminer les caractéristiques des fuites d'air des gaines d'ascenceurs et des cages d'escaliers et la résistance aux écoulements à l'intérieur des cages d'escaliers de huit bâtiments à plusieurs étages. Les résultats des essais rapportés dans cette communication fournissent des données pouvant être utilisées pour la conception des systèmes de pressurisation qui protègent les cages d'escaliers ou les gaines d'ascenseur de la contamination par la fumée durant un incendie.

No. 2413

AIR LEAKAGE DATA FOR THE DESIGN OF ELEVATOR AND STAIR SHAFT PRESSURIZATION SYSTEMS

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Smoke migration as a result of fire can contaminate elevator and stair shafts, posing a serious threat to fire fighters and occupants, particularly in high-rise buildings where the time for evacuation can be long and the fire must be fought from inside. Measures to prevent smoke contamination of elevator and stair shafts, therefore, are an essential part of the over-all fire protection system for high-rise buildings.

Pressurization of a shaft is one means of maintaining it tenable during a fire. This involves increasing the pressures inside the shaft above those of adjacent floor spaces by injecting outdoor air into the shaft with a supply fan. The direction of air flow would then be from the shaft to the floor spaces, preventing the smoke generated by a fire from migrating into the shaft. The air supplied to the shaft not only assists in preventing smoke entry but also helps to dilute smoke which might have migrated into the shaft prior to activation of the pressurization system or when several shaft doors are opened during evacuation and fire fighting.

There are various approaches to the design of pressurization systems (1,2,3,4,5 and 6), but in all designs a knowledge of the air tightness of the shaft walls is needed to calculate the supply air rate needed to achieve the required level of pressurization. Such information is not readily available at present, and hence, a research project was undertaken to obtain air leakage values of the walls of elevator and stair shafts. In addition, the pressure loss characteristics of stair shafts were determined, as the flow resistance of the winding staircase can have a significant effect on the vertical distribution of pressurization.

The elevator and stair shafts of eight multistory buildings ranging in height from 9 to 22 stories were tested, and the results are herein reported.

METHOD OF TEST

A 50,000-cfm (23.5-m^3/s) vane axial fan was used to conduct the shaft air leakage tests (Fig. 1). The fan was mounted on a trailer so that it could be transported easily to the buildings under test. The fan is equipped with variable pitched blades that permit manual control of the supply air rate. The source of power supply was either a 550-volt circuit of the building, if one was readily accessible, or a mobile generator.

The trailer and fan were placed outside and adjacent to the building. A sealed plywood box was placed on the ground floor in front of the door opening of the shaft to be tested. The elevator car was moved away from the ground floor prior to installing the plywood box to prevent the car from interfering with the air injection. The discharge side of the fan was connected to the plywood box by means of a number of 3-ft (0.914-m) diameter aluminum ducts (Fig. 2). Total pressure averaging tubes and static pressure taps were installed in the ductwork for measuring the rate of supply air. These were calibrated with pitot traverses which indicated that the accuracy of the flow measurement was within 5%.

The air leakage measurements of each shaft were conducted in two steps: firstly with all door cracks sealed with tape (between door frame and wall not sealed) and then with all tape

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removed. Each step involved pressurizing the shaft with the supply air fan at four flow rates adjusted to give shaft pressurization of up to about 0.50 in. of water (125 N/m^2). The resultant pressure differences across the shaft wall at several levels were measured with a pressure meter (diaphragm type with silicon piezo-resistive gauge; static error band of 5% full-scale output) together with the concomitant supply air rates. The air leakage measurements with all door cracks sealed give the air leakage characteristic of the shaft wall construction, and with the door seals removed, give the overall air leakage characteristic of the shaft enclosure. The difference between the two represents that of the doors.

The determination of the air leakage characteristic of the elevator shaft wall construction required, in addition, estimating the leakage flow through the top of the shaft, as it can be substantial. The leakage openings in the sub-floor of the elevator machine room, i.e., openings for vents, car cables and other elevator accessories that could not easily be covered and sealed for the test, were measured with a measuring tape, and the pressure difference across the sub-floor was recorded during the test. From these measurements the leakage flow through the top of the shaft was calculated using the equation for an orifice and substracted from the total flow through the shaft with the doors sealed to arrive at the leakage flow through the shaft wall construction.

To measure the pressure loss characteristic of a stair shaft, plastic tubes 1/4 in. (6.35 mm) in diameter were strung vertically in the stair shaft from the top, terminating at several levels so that the ends of the tubes served as pressure taps. All stair doors were sealed except for the one at the top which was left open to expose the top of the stair shaft to outdoor ambient pressure. Outdoor air was injected into the stair shaft and allowed to flow up and out through the open stair door at the top. The pressure drop inside the stair shaft together with the supply air rate were measured during the test.

RESULTS AND DISCUSSION

The descriptions of the test elevator shafts and stair shafts are given in Table 1 and 2 which also give the dimensions of both shaft and door and the type of wall construction. The average door cracks given in the tables are based on measurements of at least ten doors of each shaft with three measurements per side of each door. The estimated sizes of the opening at the top of the elevator shaft are also included in Table 1.

Air Leakage Characteristic of Elevator Shafts

The air leakage characteristics of the shaft wall of elevator shafts in terms of volume flow rate per unit wall area vs pressure difference, shown on Fig. 3, indicate considerable variation in their values. Those of masonry construction either of concrete or hollow clay tile block, including a shaft constructed front and back of cast-in-place concrete with the two sides of concrete block, gave the highest leakage values of about 1.80 cfm per sq ft (0.00914 m^3/s per m^2) of wall area at a pressure difference of 0.30 in. of water (75.0 N/m^2). Those constructed entirely of cast-in-place concrete or a combination of cast-in-place concrete on three sides and concrete block on the front side were about one-third of this value. As the cast-in-place concrete wall itself can be expected to be relatively air tight, it is likely that the leakage flow in the latter cases occurred mainly through crack openings between door frame and wall and pipe chases for electrical conduits (lights, call buttons, etc.) in the shaft walls.

The leakage openings at the top of the elevator shaft (Table 1), determined with a measuring tape, varied from 4.2 to 10.5 sq ft (0.39 to 0.97 m^2) except for 0.50 sq ft (0.046 m^2) for Elevator Shaft No. 5, whose openings in the concrete floor slab were found to be covered in part with sheet metal. The pressure differences across the top of the elevator shaft (sub-floor of elevator machine room) with the shaft pressurized were about one-half those across the shaft walls.

The air leakage values for elevator doors shown on Fig. 4 varied from 650 to 950 cfm (0.307 to 0.448 m^3/s) at a pressure difference of 0.30 in. of water (75.0 N/m^2). The average value of the flow exponent is about 0.55 which is similar to that for a flow through an orifice. The leakage values at 0.30 in. of water (75.0 N/m^2) correlate approximately with the average crack width around the door which varied from 0.19 to 0.27 in. (4.8 to 6.8 mm), as shown on Fig. 5. The air leakage value for pressure difference ΔP other than 0.30 in. of water (75.0 N/m^2) can be obtained by multiplying the value given in Fig. 5 by $(\Delta P/0.30)^{0.55}$ or $(\Delta P/75)^{0.55}$ for values in British and SI units respectively.

An ad hoc test was conducted on Elevator Shaft No. 1 to determine the effective opening formed by a combination of an open elevator door and an elevator car. A 3000-cfm (1.42 m^3/s) fan was used to pressurize the box placed in front of the open elevator door and the flow rates and the resultant pressure differences across the shaft wall were measured. From these measurements the leakage area in terms of an equivalent orifice area was calculated to be about 6.0 sq ft (0.56 m^2).

Air Leakage Characteristic of Stair Shafts

The air leakage rates of the walls of the test stair shafts are given in Fig. 6. They are in the range of the air leakage rates for walls of elevator shafts constructed of cast-in-place concrete. The variation in the air leakage rates is probably due to extraneous leakages around door frames, electrical conduits for lighting, and service panels in the walls. The relatively high air leakage rate for Stair Shaft No. 6 was probably caused by large cracks around the door frames through which the flow of leakage air was felt during the test.

The air leakage rates for the stair doors given in Fig. 7 indicate that they vary from 240 to 575 cfm (0.113 to 0.271 m^3/s) per door at a pressure difference of 0.30 in. of water (75.0 N/m^2) and that they are related to the average crack width between door and door frame which ranged from 0.08 to 0.18 in. (2.03 to 4.57 mm) (Fig. 5).

Pressure Loss Characteristic of Stair Shafts

Pressure losses inside the stair shafts were measured with the air injected into the stair shaft on the ground floor and the stair doors sealed except for the door at the top which was left open. Measured pressure losses for the test stair shafts, shown in Fig. 8 indicate that they are linear with the height of the stair shaft. Also, the total pressure losses for each stair shaft at various flow rates given in Table 3 indicate that the pressure loss is directly proportional to the square of the flow rate.

It appears that the pressure loss inside a stair shaft behaves much like that caused by friction in a rectangular air duct. An equation describing the pressure loss inside a stair shaft, therefore, was based on that for a rectangular air duct.

$$\Delta P_L = K \left(\frac{L}{D_e} \right) V_p \qquad (1)$$

where

ΔP_L = total pressure loss per floor, in. of water (N/m^2)

K = pressure loss coefficient

L = height of shaft per floor, ft (m)

D_e = equivalent diameter, ft (m)

V_p = velocity pressure, in. of water (N/m^2)

The pressure loss coefficient K is analogous to friction factor f which depends on the roughness of the interior surface of a duct.

The equivalent diameter can be calculated as follows:

$$D_e = \frac{4A}{P} \qquad (2)$$

where

A = inside horizontal cross-sectional area of shaft, sq ft (m^2)

P = outer perimeter of the inside horizontal cross-section of shaft, ft (m)

Also the velocity pressure of the flow of air at standard condition can be expressed as follows:

$$V_p = \left(\frac{Q}{4005A} \right)^2 \qquad (3)$$

where

Q = flow rate, cfm (m^3/s)

Note - when SI units are used, constant 4005 in Eq 3 is replaced by 1.29.

The values of the pressure loss coefficient K calculated from Eq 1 are given in Table 3. They are approximately constant at different flow rates for each stair shaft. The values of K ranged from 32 to 38 for the conventional stair shafts (Stair Shafts No. 1 to 7). These values compared with those for air ducts whose friction factor f varies from 0.01 to 0.05 (7) indicate that the flow resistance in the stair shaft is several orders greater than that of an air duct.

The scissor stairs differ from the conventional stair shaft in that the former contains two separate staircases in the one shaft. In calculating the K value for the scissor stair, therefore, one-half of the cross-sectional area of the shaft was taken to determine the velocity pressure. On this basis, the value of K for the scissor stair (Stair Shaft No. 8) was found to be about 15, which is less than one half that for the conventional stair shaft. It is likely that the lower value of K for the scissor stairs compared with that for the conventional stair shaft is mainly due to the difference in the number of 180-deg turns: two per floor for the conventional stair shaft and one per floor for the scissor stairs as its stair case continues in the same direction between floors.

The flow resistance of a stair shaft can also be represented by an orifice at each floor level assuming no resistance between floors. The size of the orifice can be calculated from the pressure loss coefficient K by the following equation.

$$\frac{A_o}{A} = \frac{1}{C_d \left(K \frac{L}{D_e}\right)^2} \qquad (4)$$

where

A_o = orifice area, sq ft (m^2)

C_d = coefficient of discharge for an orifice (C_d = 0.60 for turbulent flow)

This equation was obtained by equating Eq 1 and the equation for calculating pressure loss through an orifice. The calculated values of A_o/A for the test stair shafts are given in Table 3. It is seen that the size of the orifice varies from 24 to 32% of the cross-sectional area of the shaft.

The pressure difference across a shaft wall as a result of pressurization depends not only on the air leakage characteristics of the shaft walls but also on those of the walls intervening between the pressurized shaft and outside. Where only a few shafts are pressurized, the effect of the intervening walls may not be significant, but where a large number are pressurized, the pressure differences across the pressurized shaft can be less than expected, as the leakage flow would raise the pressures of the floor space adjacent to the shaft. The calculation of the pressure differences across the walls of a pressurized stair shaft is further complicated by the pressure losses that occur inside it. Its effect is to cause nonuniform pressurization of the stair shaft with the highest pressurization near the point of air injection and the least at the opposite end (1,2,3 and 4). Trial and error calculations are required to achieve a system which will give the required level of pressurization but not exceed that which will interfere with door operation. A computer program to assist in the design of pressurization systems is given in Ref (8).

CONCLUSION

The results of the air leakage tests on elevator and stair shafts of eight multistory buildings are reported. They can be used in the design of pressurization systems for the protection of elevators and stair shafts from smoke contamination in the event of a fire.

Fig. 3 gives the air leakage of walls of elevator shafts. It indicates that the leakage values for walls constructed of masonry units are considerably higher than those of cast-in-place concrete. Fig. 4 gives the air leakage rates of elevator doors, which correlated with the average crack width between door and door frame as shown on Fig. 5. Table 1 indicates that the total area of openings at the top of the shaft can be substantial; they varied from 0.5

to 10.5 sq ft (0.046 to 0.97 m^2). Field measurements indicate that the pressure difference across the openings at the top of a pressurized shaft can be taken to be one-half of that across the shaft wall. The air leakage rate of an open elevator door with the car in place can be calculated assuming an effective opening with an equivalent orifice area of 6.0 sq ft (0.56 m^2).

The air leakage rates of the walls of stair shafts given in Fig. 6 indicate that they are similar to those of the elevator shafts constructed of cast-in-place concrete, as the walls of the test stair shafts constructed of masonry were usually either parged or plastered. The variation in the air leakage rates of the walls of stair shafts could not be related to the type of wall construction as was the case for the elevator shafts. It depended, probably, on the workmanship in sealing crack openings around door frames, light fixtures and service panels in the walls. Fig. 7 gives the air leakage rates of stair doors which correlated with the average crack width between door and door frame as shown on Fig. 5.

The value of the pressure loss coefficient, K, was determined to be about 35 for the conventional stair shaft and 15 for the scissor stairs; the latter value being based only on the one stair shaft and, hence, requiring additional testing to confirm this value. As these values indicate, the internal flow resistance of a stair shaft is substantial and it must be taken into account, therefore, in designing a stair shaft pressurization system.

REFERENCES

1. DeCicco, P.R., Cresci, R.J., and Correale, W.H., "Report of Fire Tests, Analyses and Evaluation of Stair Pressurization and Exhaust in High-Rise Office Buildings," Performed for the New York City Fire Department. Center for Urban Environmental Studies, Polytechnic Institute of Brooklyn, September 1972.

2. Koplon, N.A., "Report of the Henry Grady Fire Tests," City of Atlanta Building Department, Atlanta, Georgia, January 1973.

3. Fung, F.C.W., "Evaluation of a Pressurized Stairwell Smoke Control System for a 12 Storey Apartment Building," Center for Building Technology, Institute for Applied Technology, National Bureau of Standards, Washington, D.C. NBSIR 73-277, June 1973.

4. Tamura, G.T., "Experimental Studies on Pressurized Escape Routes, "Division of Building Research, National Research Council Canada, NRCC 14566, reprinted from ASHRAE TRANSACTIONS Vol. 80, Part 2, 1974.

5. Erdelyi, B.J., "Test Results of a Ducted Stairwell Pressurization System in a High Rise Building," ASHRAE TRANSACTIONS Part I, Vol. 81, 1975.

6. Shaw, C.Y., Tamura G.T., "Design of a Stairshaft Pressurization System for Tall Buildings", ASHRAE JOURNAL, February 1976.

7. ASHRAE HANDBOOK OF FUNDAMENTALS, Chapter 5, "Fluid Flow," 1972.

8. Shaw, C.Y., Sander, D.M., and Tamura, G.T., "A Fortran IV Program to Simulate Stair-Shaft Pressurization System in Multi-Storey Buildings," Division of Building Research, National Research Council Canada, DBR Computer Program No. 38, December 1974.

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Table 1

Description of Test Elevator Shafts

Test Shaft No.	No. of Stories	No. of Cars	Shaft Inside Dimension ft x ft (m x m)	Door Opening ft x ft (m x m)	Average Crack Width of Door in. (mm)	Opening at Top of Shaft sq ft (m^2)	Wall Construction
1	17	2	7.8x19.0 (2.38x5.60)	3.5x7.0 (1.07x2.13)	0.23 (5.8)	8.3 (0.77)	cast-in-place concrete except two sides of concrete block
2	14	2	7.7x18.5 (2.35x5.64)	4.0x7.0 (1.22x2.13)	0.23 (5.8)	6.6 (0.61)	cast-in-place concrete except front of concrete block
3	12	4	7.5x36.7 (2.29x11.2)	3.3x7.0 (1.00x2.13)	0.23 (5.8)	4.2 (0.39)	cast-in-place concrete
4	6	3	8.5x22.8 (2.59x6.95)	3.5x7.0 (1.07x2.13)	0.21 (5.3)	7.1 (0.66)	concrete block
5	16	2	7.3x17.0 (2.22x5.18)	3.5x7.0 (1.07x2.13)	0.27 (6.8)	0.5 (0.05)	cast-in-place concrete
6	10	2	8.0x17.0 (2.43x5.18)	3.5x7.0 (1.07x2.13)	0.19 (4.8)	3.8 (0.35)	clay tile block
7	14	2	7.7x18.5 (2.35x5.64)	3.5x7.0 (1.07x2.13)	0.27 (6.8)	10.5 (0.97)	cast-in-place concrete except front of concrete block

Table 2

Description of Test Stair Shafts

Test Shaft No.	No. of Stories Served	Shaft Inside Dimension ft x ft (m x m)	Door Opening ft x ft (m x m)	Average Crack Width of Door in. (mm)	Wall Construction
1	19	7.7x17.0 (2.35x5.18)	3.0x7.0 (0.914x2.13)	0.08 (2.0)	cast-in-place concrete, parged
2	23	6.7x14.2 (2.04x4.33)	3.0x7.0 (0.914x2.13)	0.13 (3.3)	cast-in-place concrete, parged
3	28	8.0x13.7 (2.44x4.17)	3.0x7.0 (0.914x2.13)	0.16 (4.0)	cast-in-place concrete, parged
4	23	7.4x14.6 (2.25x4.45)	3.0x7.0 (0.914x2.13)	0.12 (3.0)	cast-in-place concrete, parged
5	15	10.1x18.6 (3.08x5.67)	5.0x7.2* (1.52x2.19)	0.11 (2.8)	cast-in-place concrete except front and back of concrete block
6	17	7.4x13.5 (2.26x4.11)	3.0x7.0 (0.914x2.13)	0.18 (4.6)	cast-in place concrete, parged
7	11	9.4x16.4 (2.86x5.00)	3.0x6.8 (0.914x2.07)	0.14 (3.5)	clay tile block plastered
8**	12	3.9x34.5 (1.19x10.5)	3.0x7.0 (0.914x2.13)	0.18 (4.6)	cast-in-place concrete except front of clay tile block

* double door

** scissor stair shaft, all others are conventional stair shafts

Table 3

Pressure Loss Coefficients of Stair Shaft

Test Shaft No.	Height ft. (m)	Flow Rate cfm (m^3/s)	Pressure Loss in. of water (N/m^2)	Pressure Coefficient K	A_o/A* per floor
1	232 (70.7)	23,000 (10.8)	1.65 (411)	38.6	0.26
2	250 (76.2)	9,380 (4.43)	0.59 (147)	35.8	0.26
		19,400 (9.15)	2.64 (658)	37.1	0.24
3	311 (94.8)	10,500 (4.95)	0.59 (147)	33.5	0.28
		16,000 (7.55)	1.32 (329)	32.3	0.29
		19,000 (8.97)	1.91 (476)	33.0	0.28
4	250 (76.2)	15,000 (7.08)	1.16 (289)	37.9	0.26
		20,000 (9.44)	1.94 (483)	35.5	0.29
5	178 (54.2)	15,000 (7.08)	0.20 (50)	37.5	0.29
		19,000 (8.97)	0.36 (90)	37.9	0.29
		22,400 (10.57)	0.46 (115)	37.6	0.29
6	170 (51.8)	14,500 (6.84)	0.78 (194)	33.6	0.28
		20,200 (9.53)	1.45 (361)	32.2	0.29
		24,800 (11.70)	2.05 (511)	30.1	0.30
7	139 (42.4)	15,200 (7.17)	0.23 (57)	33.2	0.29
		19,800 (9.34)	0.41 (102)	34.2	0.29
		25,600 (12.08)	0.67 (167)	33.8	0.29
8**	167 (50.9)	15,100 (7.12)	0.28 (70)	15.3	0.31
		20,000 (9.44)	0.49 (122)	15.1	0.32
		25,600 (12.08)	0.76 (189)	14.5	0.33

* A_o = flow resistance in terms of equivalent orifice area per floor, sq ft (m^2)
A = cross-sectional area of shaft, sq ft (m^2)

** scissor stair shaft, all others are conventional stair shafts

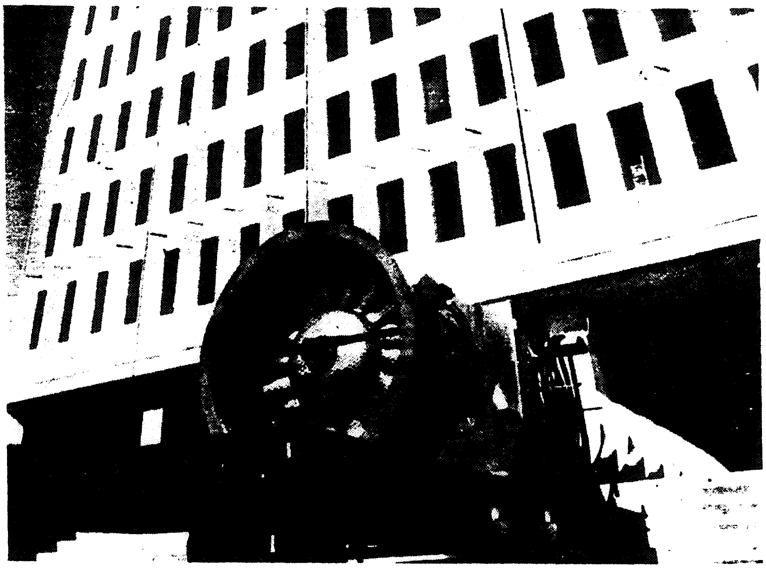

Fig. 1 Air supply fan and ductwork outside test building

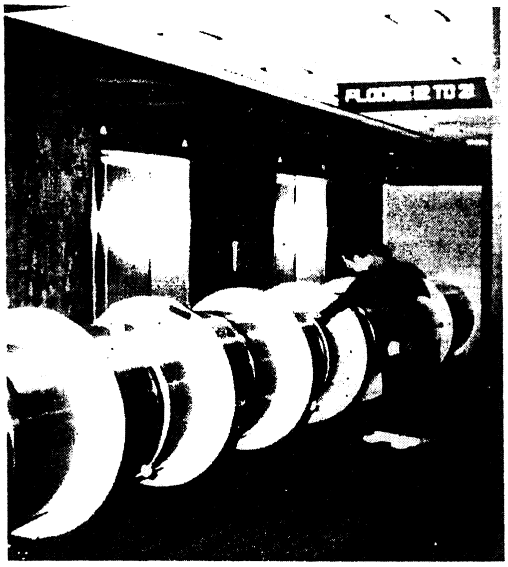

Fig. 2 Air supply system connected to test elevator shaft

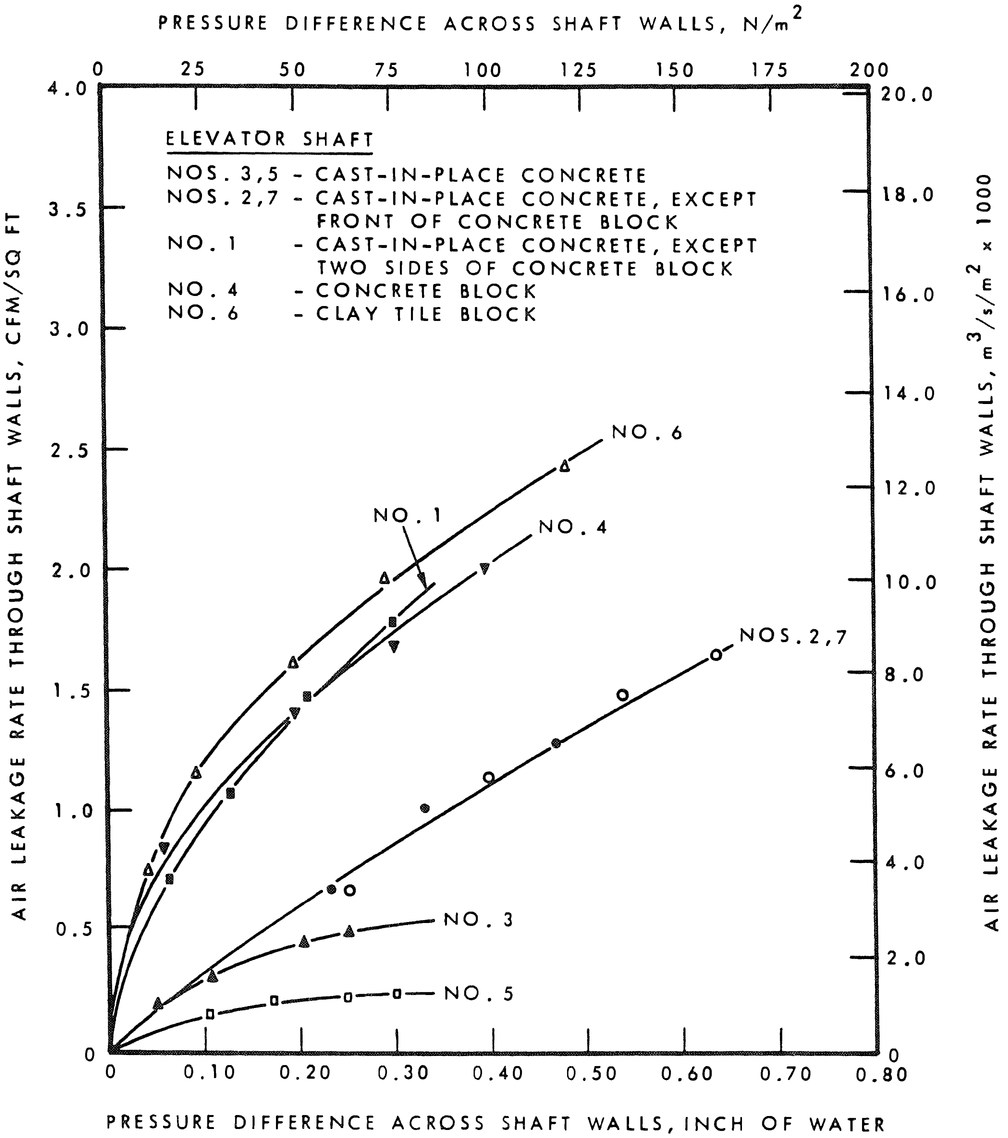

Fig. 3 Air leakage rates of elevator shaft walls

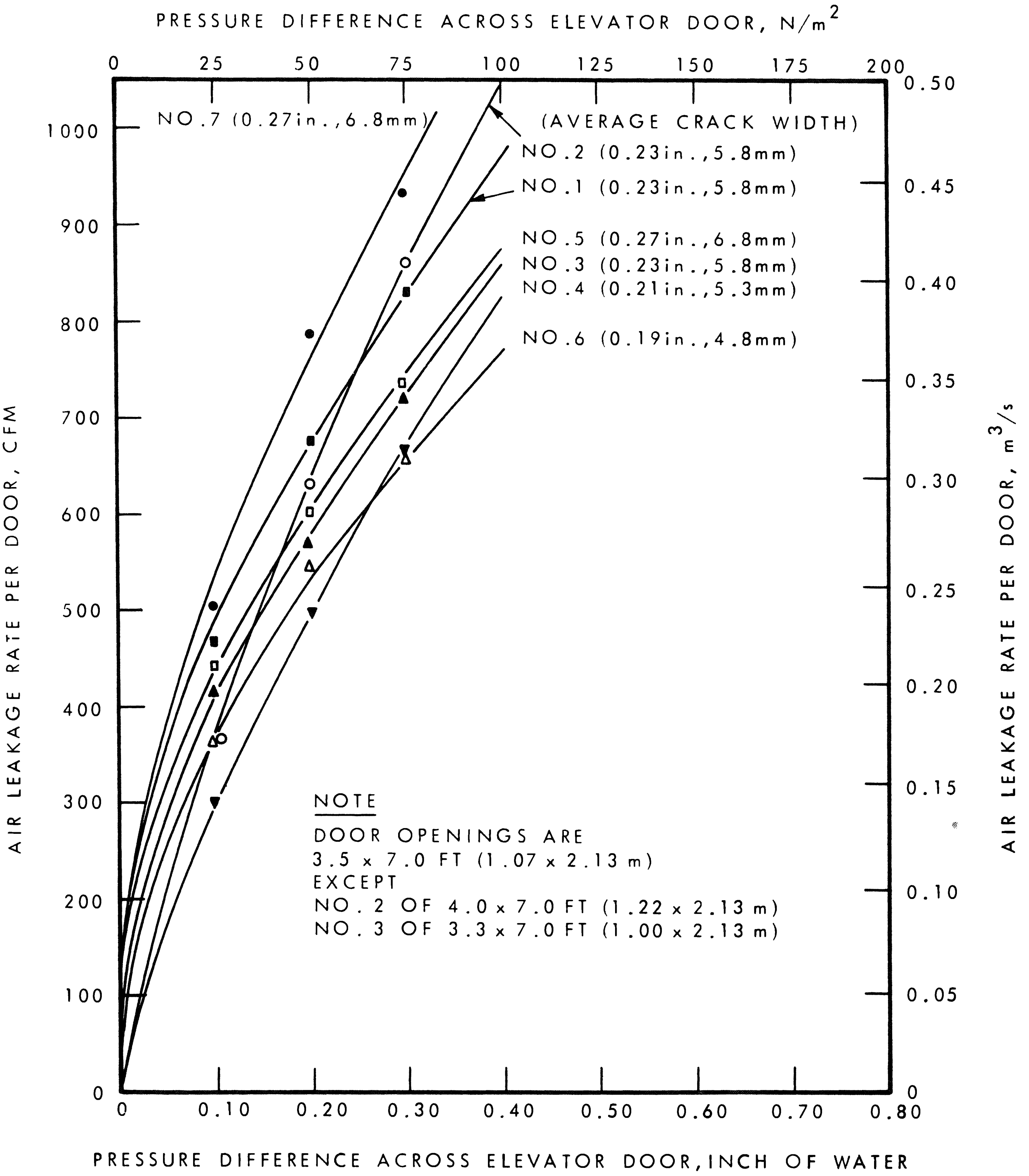

Fig. 4 Air leakage rates of elevator door

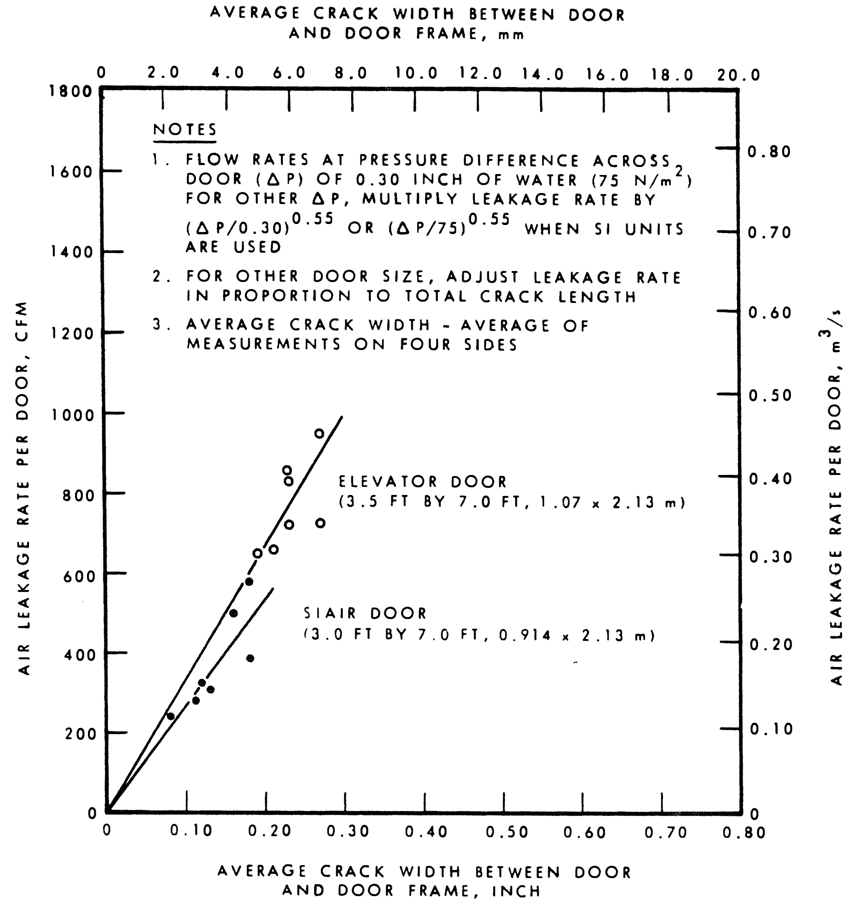

Fig. 5 Air leakage rate of door vs average crack width

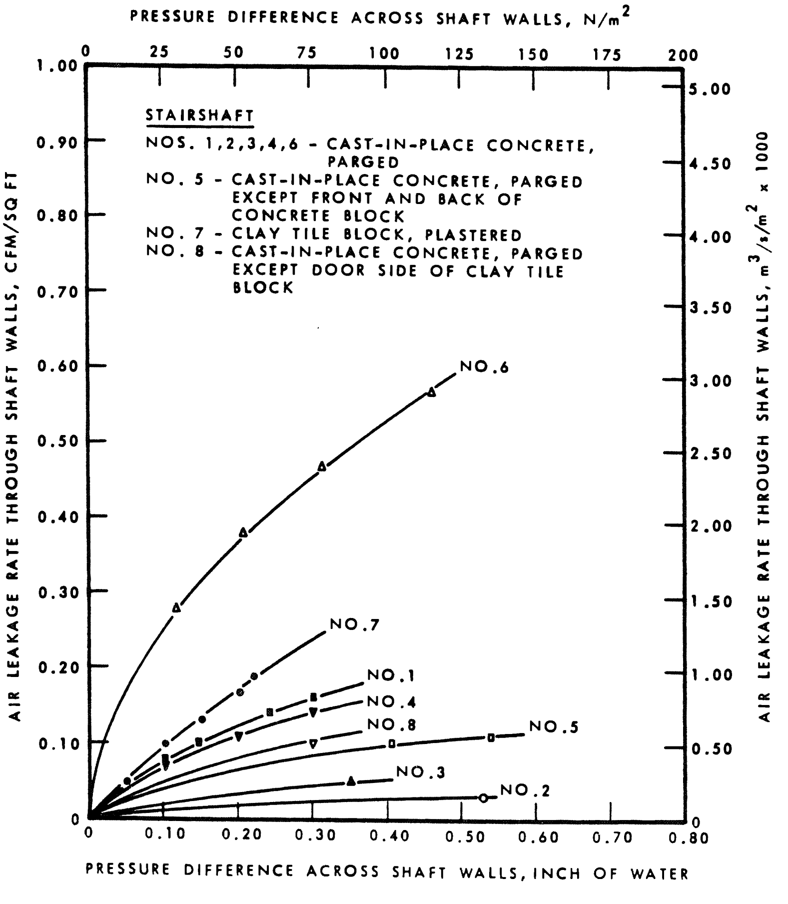

Fig. 6 Air leakage rates of stairshaft walls