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Experimental Studies on Pressurized Escape Routes

by
George T. Tamura

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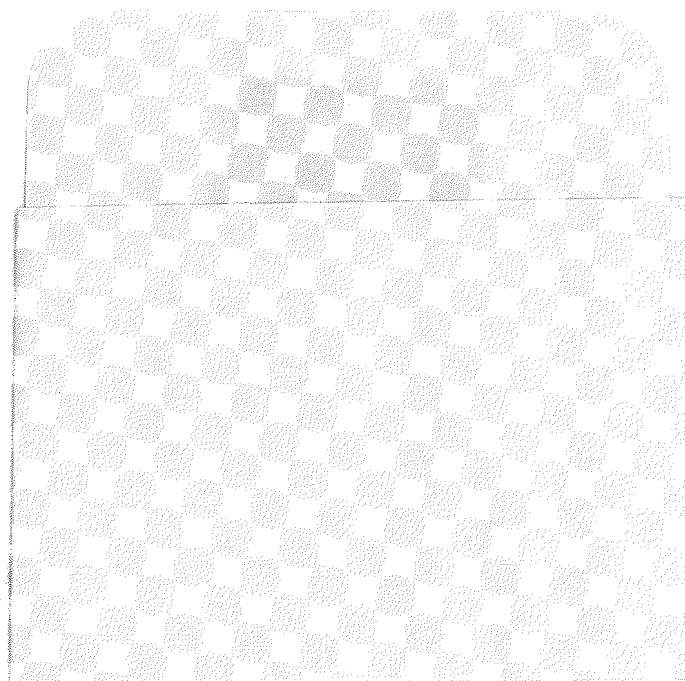
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ETUDES EXPERIMENTALES DES ISSUES SOUS PRESSION

SOMMAIRE

L'auteur présente les résultats d'essais effectués sur deux édifices en vue d'évaluer l'efficacité de la pressurisation pour empêcher l'effondrement des puits d'escalier en cas d'incendie. On vérifie l'effet de garder quelques portes ouvertes et l'effet d'une injection d'air à la base ou au sommet du puits. L'auteur recommande l'injection d'air à plusieurs niveaux afin d'assurer une pressurisation uniforme du puits d'escalier et un écoulement d'air dans l'ensemble du puits. On présente également les données des essais concernant l'étanchéité à l'air des murs et des portes des puits d'escalier ainsi que la résistance à l'écoulement à l'intérieur du puits.



EXPERIMENTAL STUDIES ON PRESSURIZED ESCAPE ROUTES

GEORGE T. TAMURA

Member ASHRAE

The pressurization of stair shafts as a means of providing smoke-free escape routes during a fire has received much attention in recent years by a number of investigators and code authorities (1-11). This method has special application to high-rise buildings as evacuation time can be long and fire fighting difficult; hence safe vertical passageways must be assured for the duration of a fire. It entails injecting outside air into the stair shaft to establish flow from it to adjacent spaces, thus preventing entry of smoke into the stair shaft as well as dispersing any smoke within it.

The design of a stair pressurization system requires information on the airtightness of walls and doors of stair shafts and on the resistance to air flow through the stair shaft itself. The tests described in this paper were conducted to obtain this information for two high-rise buildings. It must be anticipated that several stair doors will be open during a fire to permit evacuation and fire fighting. This reduces the pressures in the stair shaft and can adversely affect the performance of the smoke control system. The effect of having some stair doors open was also checked, therefore, as well as the differences that occur when air is injected at the top or bottom of the shaft.

DESCRIPTION OF BUILDINGS AND TEST PROCEDURE

The stair shaft of building A serves 23 stories (including one basement floor) and has a conventional stairway. The walls of the stair shafts in building A are constructed of cast-in-place concrete. Building B differs in that its stair shaft serves 37 stories (5 of which are underground), the stairs are the scissor-type (two stairs in a single shaft), and the walls of the shaft are of concrete blocks. The doors between the stair shaft and the floor spaces are the same in the two buildings. The dimensions of the stair shafts and the buildings are given in Table I.

TABLE I
Description of Stair Shafts, Buildings A and B

	<u>Building A</u>	<u>Building B</u>
Building plan	126 ft by 146 ft	107 ft by 146 ft
No. of stair shafts	2	2
Floors served above grade	22	32
Floors served below grade	1	5
Typical floor height	10 ft, 7 in.	11 ft, 6 in.
Over-all height	258 ft	425 ft
Shaft size	6.75 by 14.25 ft	8.5 ft by 31.0 ft
Typical door size	36 in. by 84 in.	36 in. by 84 in.
Construction	conventional, cast-in-place concrete, plaster finish	scissors, concrete blocks, paint finish

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As building A is not provided with a stair shaft pressurization system, the tests were conducted using a mobile fan unit located outside the building entrance and connected to the stair shaft at ground level by several lengths of aluminum duct. The fan, mounted on a trailer, is a vane axial type with variable pitch blades, which permit variation in fan flow from zero to 50,000 cfm. The flow rate of supply air was measured with a velocity-pressure averaging tube and static pressure taps installed in a duct section between the fan and the building.

Building B has a pressurization system for each stair shaft, which is located on the 32nd (mechanical) floor, the top floor. It consists of a vane axial fan, motorized dampers and associated duct-work. Each supply fan is rated at 22,000 cfm at 2.0 in. of water static pressure. Outside air is drawn from the cooling tower enclosure and delivered to each stair shaft through a 3- by 5-ft opening in the wall at the 32nd floor. The pressurization system can be activated either by a pull alarm or a signal from a smoke detector located at the top of each stair shaft.

Initial tests were conducted to determine the airtightness of the stair-shaft enclosure and the pressure loss characteristic of the stairway. To isolate air leakages through stair doors from those of the wall construction, leakage cracks of all stair doors were sealed with tape; the cracks between frame and wall were not sealed. The stair shafts were pressurized with various supply air rates and the concomitant pressure differences across the shaft walls were measured at several levels. The tests were conducted with the stair doors sealed followed by tests with them unsealed.

Plastic tubes 1/4 in. in diameter were strung vertically in the stair shaft from the top terminating at several levels so that the ends of the tube could serve as pressure taps to measure the pressure losses within the stair shaft. The difference in pressures between each pressure tap and the top of the stair shaft was measured with a pressure meter (diaphragm type with silicon piezo-resistive gauge; static error band of $\pm 1.5\%$ of full-scale output).

Tests were conducted with the pressurization systems in operation and with the stair and entrance doors open at or near grade level. This was followed by a series of tests conducted with various combinations of open stair doors. During each test, pressure differences across the stair doors, pressure losses within the stair shafts, and the supply air rates were measured. In addition, the air velocity through each stair door opening was measured with a hot wire anemometer. The difference in pressures between outside and the stair shaft at the top and at grade level was also measured to relate the stair-shaft pressures to outside pressures.

RESULTS AND DISCUSSION

The rate of air supply required to pressurize a stair shaft to a desired level depends upon the airtightness of the shaft enclosure. Tests conducted with all of the stair doors sealed give the airtightness value of the shaft wall construction, whereas the test conducted with the door seals removed yields the over-all airtightness value of the shaft enclosure. The difference in the two readings is the airtightness value of the stair doors.

The airtightness values in terms of equivalent orifice area in square feet per floor were as follows:

	Building A	Building B
Shaft wall	0.01	0.18
Stair door	0.25	0.24
TOTAL	0.26	0.42

It is evident that the shaft walls of building A are considerably tighter than those of building B. The former are constructed of cast-in-place concrete, whereas the latter are constructed of concrete blocks. In addition, a number of service panels and pipes in the stair shaft of building B probably contributed to its relatively high leakage value. The airtightness values of the stair doors of buildings A and B, however, were similar. This is consistent with the measurements of the crack widths between door and frame which were similar for both build-

ings with average values of 3/8 in. at the bottom and 3/32 in. for the remaining three sides.

The resistance to flow caused by the path formed by the shaft wall and staircase can affect the uniformity of vertical pressurization in the stair shaft. The pressure gradient inside the stair shaft is also affected by the change in flow rate by leakage flow through the shaft wall and the column weight of air, assuming that there is no temperature gradient and that the cross-sectional area of the stair shaft is constant for the height of the shaft (1, 2). To minimize the effect of the leakage flow, pressure losses of the stair shaft of building A were measured with all stair doors sealed making the shaft wall virtually airtight. The pressure losses measured are thus due to the flow resistance of the stair shaft, as the effect of column weight of air is also eliminated with the use of vertical runs of plastic tubes as previously described. The stair shaft was pressurized with supply air rates of 9,000 and 18,000 cfm at grade level with the stair door at the top level open. The flow rates measured at the entrance and exit of the stair shaft indicated leakage flow through the shaft walls of less than 5% of the supply air rates.

The measurement of the pressure loss characteristics of the scissor stairs of building B was not attempted as its shaft walls were found to be quite leaky and hence a realistic value could not be expected. Tests were conducted, however, on the scissor stairs of an 11-storey building (building C) whose shafts are constructed of cast-in-place concrete. Measurements of the airtightness of these shaft walls gave leakage values similar to those of building A. With the stair doors sealed, the stair shaft was pressurized with flow rates of 15,000, 20,000 and 25,000 cfm.

The pressure loss characteristics of the stair shafts for both buildings A and C were linear with height; the pressure losses varied with the square of the supply air rates. Fig. 1 gives the relationship between the supply air rates and the average pressure losses per floor, from which the pressure loss factors were calculated. The pressure loss factor as defined in this paper is given by the following equation:

$$K = \frac{\Delta P}{N(VH)} \quad (1)$$

where

K = pressure loss factor, per floor

ΔP = pressure loss, in. of water

N = number of floors

VH = velocity head, in. of water

The value of VH is based on the air flow rate divided by the full cross-sectional area of the conventional stair shaft, and one-half the cross-sectional area of the scissor stair which contains two separate stairways.

The calculation of pressure loss factors yielded values of 45 and 28 for the conventional stair shaft (building A) and the scissor stair shaft (building C) respectively.

The scissor stair shaft differs from that of the conventional stair in that the stairway continues in the same direction between floors, whereas, in the conventional stair shaft the stairway makes a 180-deg turn mid-way between floors. The number of 180-deg turns in the conventional stair shaft, therefore, would be twice as great as that for the scissor stair serving the same number of floors. The conventional stair shaft usually has no party wall at the inner railings, whereas the staircase of the scissor stair is enclosed by a wall on both sides of the tread. The size of the flow channel for the scissor stair is, therefore, much less than for the conventional stair shaft. The values of pressure loss factors can facilitate the calculations of pressure losses in a pressurized stair shaft. Such calculations are necessary in the design of a stair pressurization system as high pressure losses within a stair shaft can

result in excessive pressure differentials across the stair doors, which will interfere with their operation.

Additional test data are required to determine the effect of such parameters as the size of well between inner railings, direction of vertical flow, and staircase configuration.

Air Injection Into the Stair Shaft at the Bottom (Building A)

For all of the tests the single stair shaft of building A was pressurized with outside air supplied from the mobile fan unit ducted to the stair door opening on the ground floor. The supply air rate of 20,000 cfm was based on the intended uniform pressurization of 0.10 in. of water assuming no pressure losses with all but one stair door closed. The outside temperature during the tests was about 50 F.

Test No. A1 was conducted with the stair and freight entrance doors on the basement level open followed by test No. A2 with only the stair door on the 22nd (mechanical) floor open. During both tests the building air-handling systems were in normal operation. The resultant pressure difference readings across the stair doors for both tests, given in Fig. 2, show that the pressure difference patterns for the two tests differ significantly. For test No. A1 the pressure differences across the stair doors from the first floor to the 21st floor varied from 0.10 to 0.20 in. of water, whereas for test No. A2 they varied from 1.3 to -0.3 in. of water. The total pressure drops inside the stair shaft from the first to the 22nd floor were 0.07 and 1.68 in. of water for test Nos. A1 and A2, respectively.

The nonuniformity of pressurization can be attributed to the pressure loss characteristic of the stair shaft. This can be significant for high flow rates as in test No. A2 with pressure differences across the stair doors on the lower floors that are much greater than the maximum permissible pressure difference with regard to ease of door operation of 0.40 in. of water (3). With a flow rate of 13,100 cfm through the stair door opening on the basement floor, the upward flow rate for test No. A1 was about one third of that for test No. A2 and hence the pressurization was much more uniform. Cresci (2) and Koplon (4) reported similar results from tests conducted on pressurized stair shafts.

The pressure difference of 0.56 in. of water across the stair door of the 22nd (mechanical) floor for test No. A1 (point a of Fig. 2) indicates that the pressures on this floor are lower than those of the typical floors by 0.46 in. of water. This was probably caused by pressurization on the typical floors (0.18 in. of water) and suction on the mechanical floor (0.25 in. of water) with the operation of the building air-handling systems. This would explain the negative pressure differences across the stair doors above the 16th floor for test No. A2 as the stair-shaft pressures would tend to decrease and approach those of the mechanical floor with the stair door open on that floor. These tests indicate that a large opening at the top of the stair shaft or substantial mechanical exhaust at the top with air injection at the bottom can lead to excessive stair-shaft pressurization at lower levels and to inadequate pressurization at upper levels.

Test No. A3 was conducted with the building air-handling systems shut down and with the stair and freight entrance doors on the basement floor open. All other stair doors were closed. With the stair shaft pressurized the flow rate through the open stair door on the basement floor was 14,200 cfm giving an upward flow rate of 5,800 cfm in the stair shaft. The pressure characteristics of the two stair shafts, floor space and outside caused by building stack action and stair-shaft pressurization are shown in Fig. 3. The horizontal distances between the stair shaft and the floor space pressure characteristics represent the pressure differences across the stair doors. Similarly, the horizontal distances between the floor space and outside pressure characteristics represent the pressure differences across the exterior walls.

The neutral plane of the building is located at about the 13th floor, below which the pressures of the floor spaces are higher than those of stair shaft No. 2 (not pressurized) and above which the reverse occurs. The pressures of stair shaft No. 1 (pressurized) are, as expected,

higher than those of the floor space and outside for the entire height of the shaft. The pressure differences across the stair doors on the typical floors varied from 0.150 to 0.200 in. of water, which are greater than those obtained with the building air-handling systems in normal operation (test No. A1); the pressure difference across the stair door of the 22nd (mechanical) floor, however, was much lower. It would appear that the higher leakage rate of the shaft wall at this floor with the air-handling systems operating probably resulted in pressure differences across the stair doors of the typical floors which were lower than those with air-handling systems shut down.

With injection of untempered outside air during cold weather, the stair-shaft temperatures can be much lower than those of the surroundings. To investigate this, air temperatures of stair shaft No. 1 were measured at several levels one-half hour after the start of test No. A3; the vertical temperature gradient is shown in Fig. 4. The rate of increase in air temperature is the greatest at the point of air injection; it decreases with distance away from this point as the air temperature approaches the inside ambient temperature.

Tests Nos. A4 and A5 were conducted to investigate the performance of the stair pressurization systems with other stair doors open in addition to the one on the basement floor. All building air-handling systems were shut down as in test No. A3. It was assumed that during a fire the exit stair door at or near grade level and the stair door on the fire floor could be expected to be open for an extended period. With this in mind, test No. A4 was conducted firstly with the stair door at the 4th floor open and secondly with the stair door at the 16th floor open, the two floors representing a fire at low and high levels.

The pressure differences across the stair doors for both test conditions are shown in Fig. 5 together with those of test No. A3, during which all stair doors above grade were closed. There was a substantial decrease in pressure difference when the stair doors were opened. The average air velocities through the open stair doors were 265 fpm (5300 cfm) and 180 fpm (2600 cfm) for the 4th and 16th floor respectively. A minimum acceptable air velocity of 200 fpm is suggested in Ref 5 to prevent smoke from entering the stair shaft.

Test No. A5 was conducted with the stair doors on floors 4, 7, 8, 10, 11, 13, 14, 16, 17, 19 and 20 open to simulate evacuation. The pressure differences across the stair doors up to the 4th floor were similar to those with only the stair door on the 4th floor open. Above the 4th floor, however, pressure differences were considerably less: values varied from 0 to 0.015 in. of water (Fig. 5). The average flow velocities through the door opening were 275, 70, 50 and 12 fpm for floors 4, 10, 16 and 20 respectively. These values suggest that the effectiveness of the stair-shaft pressurization system with air injection at the bottom is not affected when several stair doors are opened above the fire floor but is adversely affected when several stair doors are opened below the fire floor. A separate test with stair doors of floors 3, 4 and 5 open resulted in an average flow velocity of 120 fpm through the stair door opening of the 4th floor. In assessing these results in the context of evacuation it should be borne in mind that the period during which each stair door other than the ones on the exit and fire floors is open is only a few minutes (the time taken by the occupants to vacate the floor).

Air Injection at Top of Stair Shaft, Building B

The scissor stairs of building B were pressurized with the two separate pressurization systems located at the 32nd (mechanical) floor. Although the size of both fans is the same, at the time of test the flow capacities were different as the one fan had more blades than the other. The outside temperature was 30 F during the tests.

Test No. B1 was conducted with the building air handling systems shut down and with all stair doors closed. Supply air rates were 16,500 cfm and 14,200 cfm for stair shafts Nos. 1 and 2, respectively. Pressure differences across the stair doors of stair shaft No. 1 are shown in Fig. 6, which shows that the pressure differences across the stair doors are much greater at upper levels than those at lower levels. This is associated with the pressure losses in the stair shaft also shown in Fig. 6 caused by the flow resistance of the stairway

resulting in shaft pressures that are substantially greater at upper levels than those at lower levels. Pressure differences across stair doors were less than 0.40 in. of water except for the top two typical floors and the mechanical floors. The pressure losses, and hence the variation in the pressure differences across the stair doors, would have been greater if the stair shaft had been the conventional type.

From Fig. 7, which shows the pressure characteristics of the floor space, stair shafts Nos. 1 and 2 and outside, it can be seen that the pressures of stair shaft No. 1 are higher than those of stair shaft No. 2 due to the higher supply air rate for the former. The neutral plane of the building with the stair-shaft pressurization systems off was at the 26th floor level. With the stair-shaft pressurization system on, the floor space pressures also increased which resulted in the lowering of the neutral plane to the 16th floor level (Fig. 7). The extent of indirect pressurization of the floor spaces would depend upon the airtightness of the exterior walls and those of the walls of the stair shaft as they comprise the resistance to flow in series from the stair shaft to the exterior. The resultant pressure differences across the stair doors would depend, therefore, on the airtightness of the exterior walls as well as that of the walls of the stair shaft.

Air temperatures of stair shaft No. 1 were measured one-half hour after the start of test No. B1. These are shown in Fig. 8 which shows a similar characteristic to those obtained for building A (Fig. 4). During cold weather, the pressurization of the stair shaft with untempered outside air can result in uncomfortable conditions in the stair shaft on several floors extending from the region of air injection.

Test No. B2 was similar to test No. B1 except that the stair and entrance doors on the first floor were open. As shown in Fig. 6 the pressure differences across the stair doors were lower for this situation than they were for test No. B1. The average air velocities through the open stair doors were 130 and 125 fpm for stair shafts Nos. 1 and 2 respectively.

Test No. B3 was also conducted with the stair and entrance doors on the first floor open. In addition, the stair door on the 28th floor for stair shaft No. 1 and stair doors on the 24th to 28th floors inclusive for stair shaft No. 2 were also open. The supply air rates increased from 16,500 cfm to 19,000 cfm for stair shaft No. 1 and from 14,200 cfm to 16,200 cfm for stair shaft No. 2. Opening of stair doors at upper levels apparently reduced the system resistance which resulted in an increase in the fan delivery. Stack action during cold weather can also affect the fan delivery. The flow rate is decreased by a fan located at the top and increased by a fan located at the bottom of a building.

Pressure differences across the stair doors given in Fig. 9 are, below the 28th floor, less than 0.08 in. of water for both stair shafts. As the air velocities across the stair door openings on the first floor were low and could not be accurately measured, the flow patterns were checked with smoke traces. In both stair shafts air flowed into the shaft through the lower part of the opening and out above it. In addition, the stair doors of the 3rd floor for both stair shafts were also opened. The direction of flow for these openings was from the stair shafts to the floor spaces for the entire opening for stair shaft No. 1 and up to 6 in. from the top of the stair door for stair shaft No. 2, above which the flow direction was indeterminate.

The pressure characteristics for test No. B3 are shown in Fig. 10. Comparison of this Figure with Fig. 7 for test No. B1 shows that with several doors opened the pressures of the stair shafts are decreased and those of the floor spaces are increased with the neutral plane lowered from the 16th to the 4th floor level. This was caused by an increase in the pressurization flow and a decrease in the resistances to flow of the stair-shaft walls relative to those of the exterior walls.

CONCLUSIONS

1. The supply air rate based on uniform pressurization of 0.10 in. of water with one stair door open and all others closed provides sufficient pressurization to maintain the stair

shaft tenable when the stair doors on the fire floor and ground floor are open. These doors can be expected to be open for an extended period during a fire.

2. A substantial decrease in stair-shaft pressurization and a possibility, therefore, of stair-shaft contamination can be expected if several additional doors are open. These doors are likely to be open, however, for a much shorter duration; the time for each door in the open position is that required by the occupants to vacate a floor.
3. The secondary objective of stair-shaft pressurization is to provide adequate flow for dilution throughout the stair shaft as there is a possibility of its being contaminated by smoke. Air injection at the bottom of the stair shaft results in a substantial loss of supply air through the open exit door. When air is injected at the top, the resultant pressure differences across the stair doors cause a high rate of leakage flow at upper levels in addition to creating problems with operation of the stair doors on these floors.
4. The best approach would appear to be to inject air at several levels rather than only at the top or bottom. In this way a substantial flow of air for dilution throughout the stair shaft and a more uniform pressurization can be achieved. The number of outlets and locations for air injection should be such that pressure differences across the stair doors are between 0.10 to 0.40 in. of water with all stair doors closed except for the one on the ground floor. Relief dampers should be considered if no provision is made for ensuring continuous opening of the stair door at the ground floor level during a fire. For very tall buildings, it may also be necessary to treat the stair shaft as a number of segments, i.e., provide a separate pressurization system for each compartment.
5. The air leakage rates of the stair doors of both test buildings were similar. Those of the shaft walls of cast-in-place concrete were negligible whereas those of the shaft walls of concrete blocks were substantial. The pressure loss factors were 45 and 28 for the conventional and scissor stair shafts respectively. Such data, which at present are sparse, are required in the design of a stair-shaft pressurization system.

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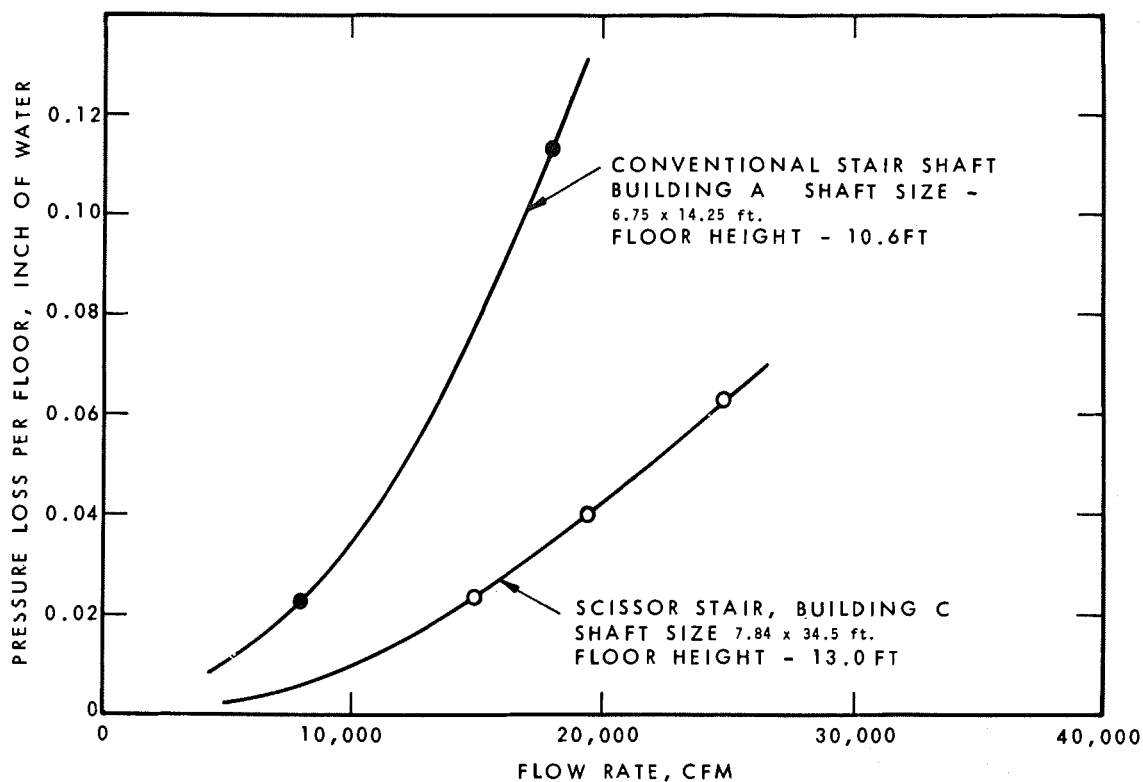


Fig. 1 Pressure loss characteristic of stair shafts

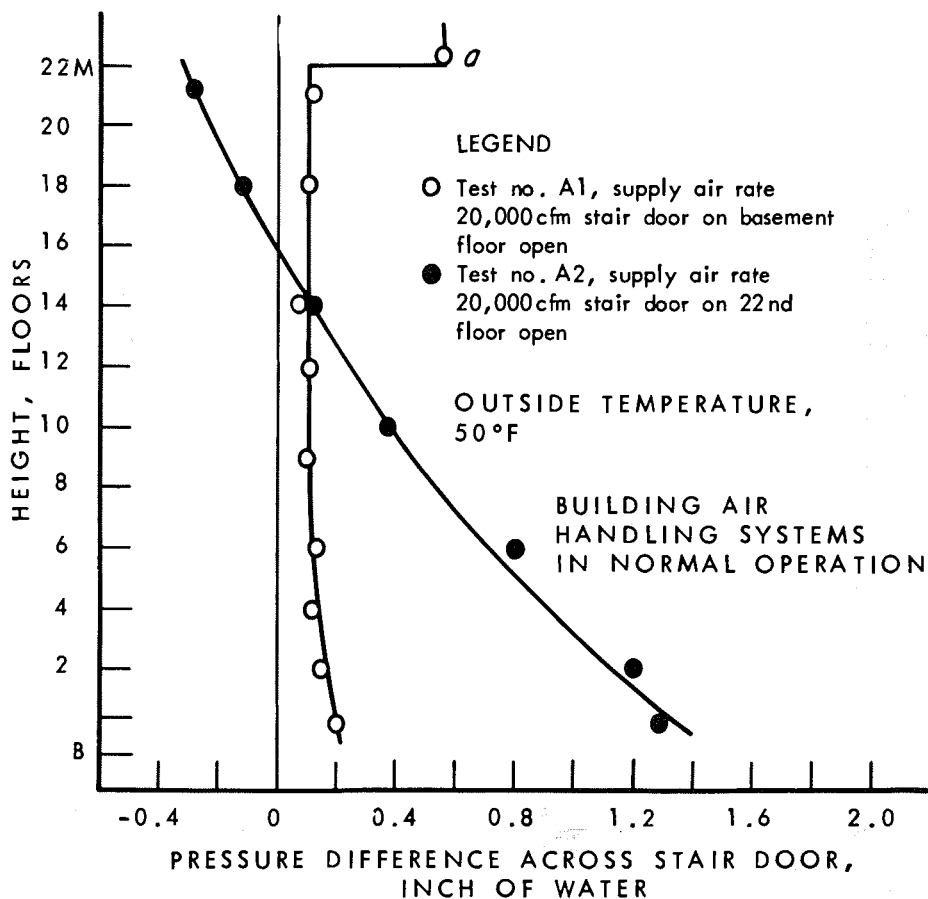


Fig. 2 Pressure differences across stair doors for test No. A1 and test No. A2 of building A

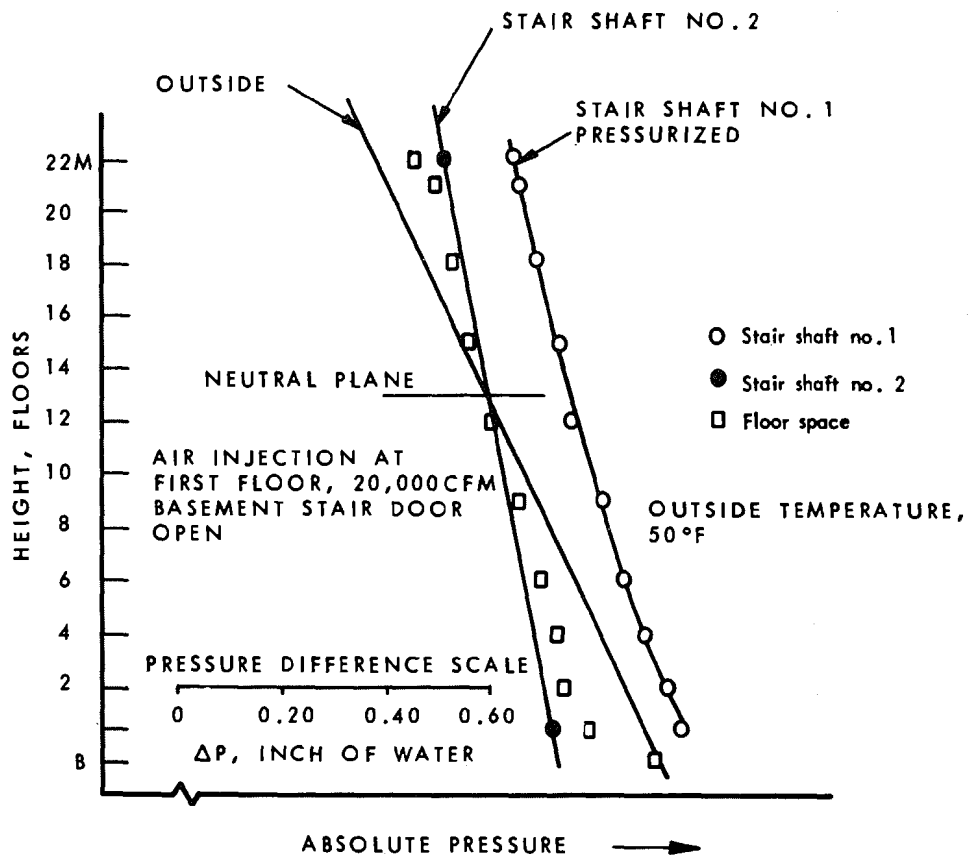


Fig. 3 Pressure characteristics with stair shaft No. 1 pressurized, test No. A3 of building A

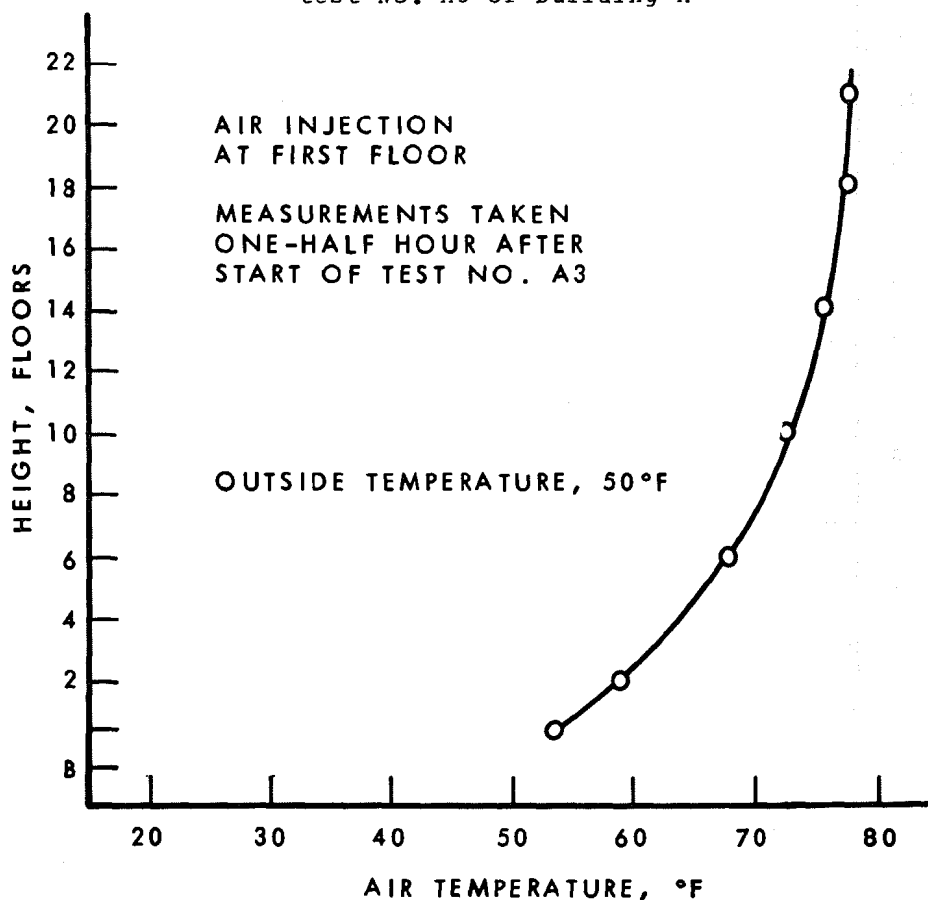


Fig. 4 Air temperatures of stair shaft No. 1 of building A during test A3

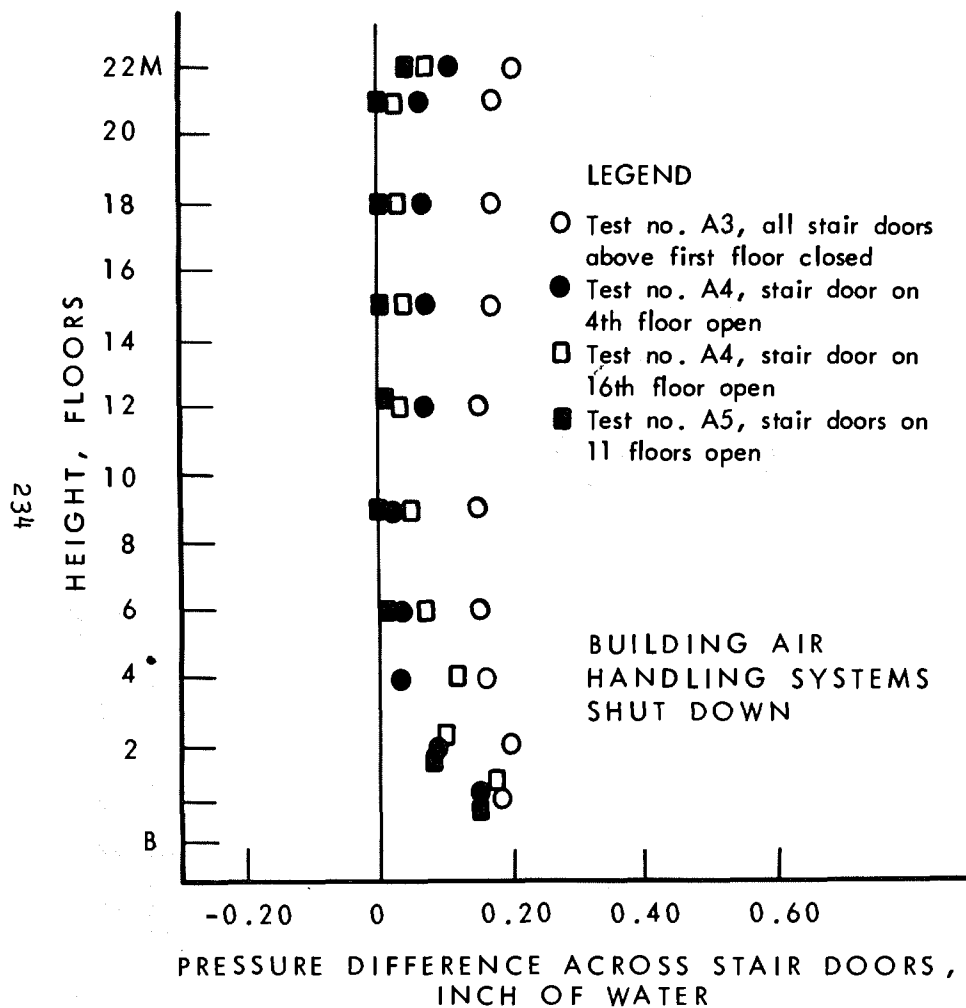


Fig. 5 Pressure differences across stair doors for test No. A4 and test No. A5 of building A (open door tests)

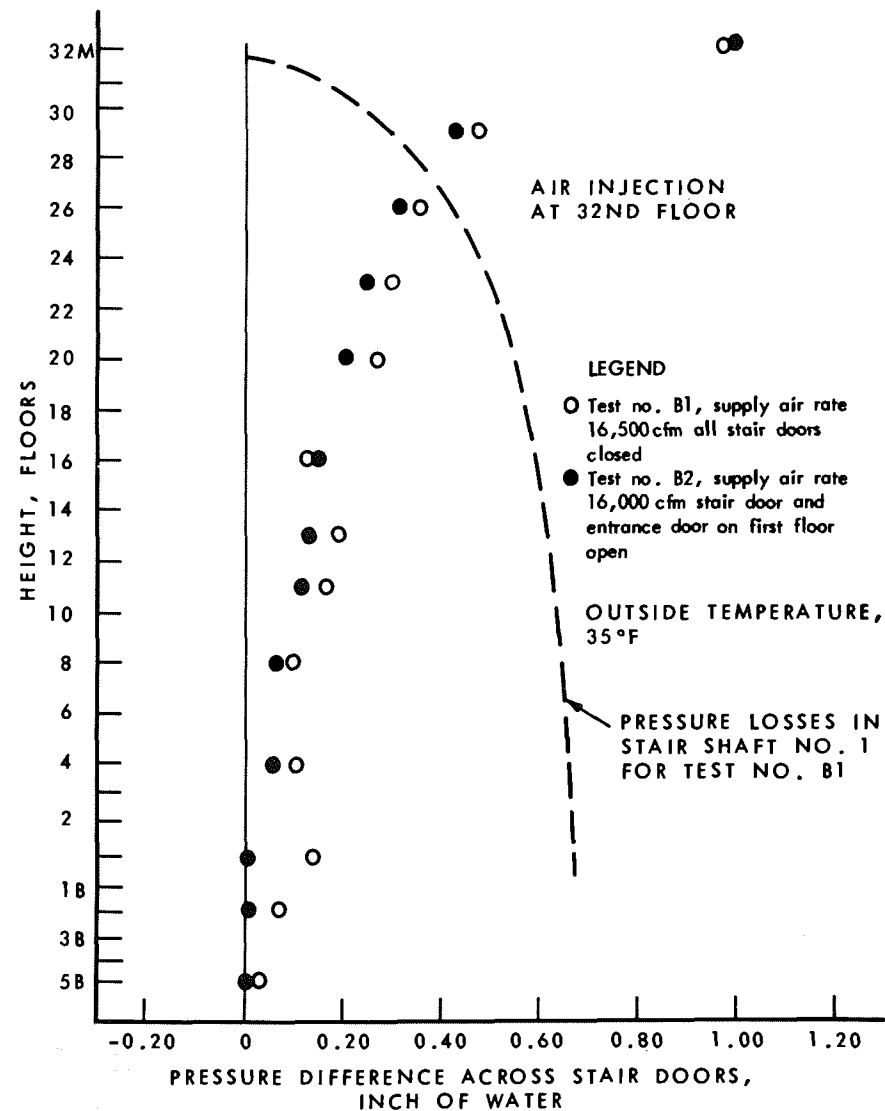


Fig. 6 Pressure differences across stair doors of stair shaft No. 1 test No. B1 and test No. B2 of building B

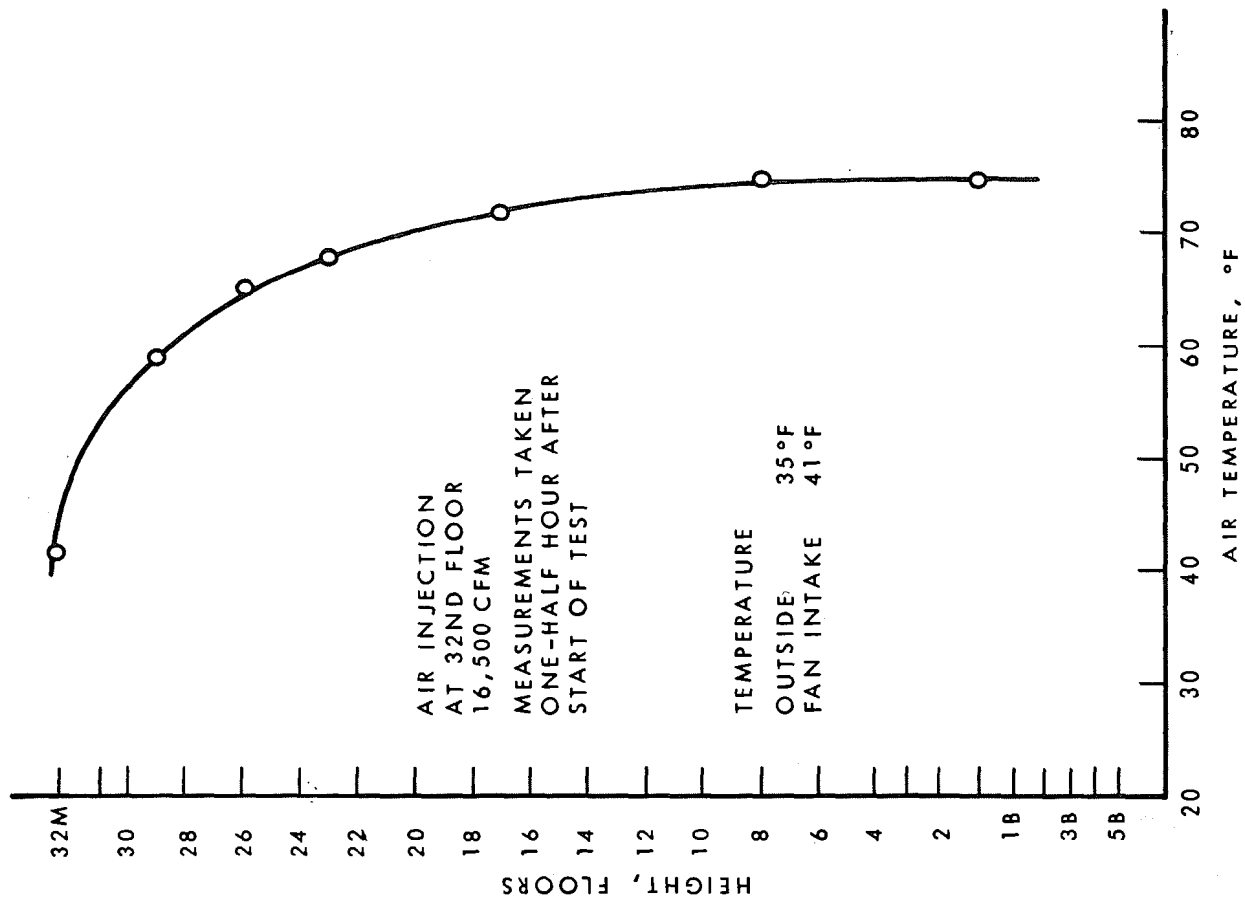


Fig. 8 Air temperature of stair shaft No. 1 of Building B during test No. B1

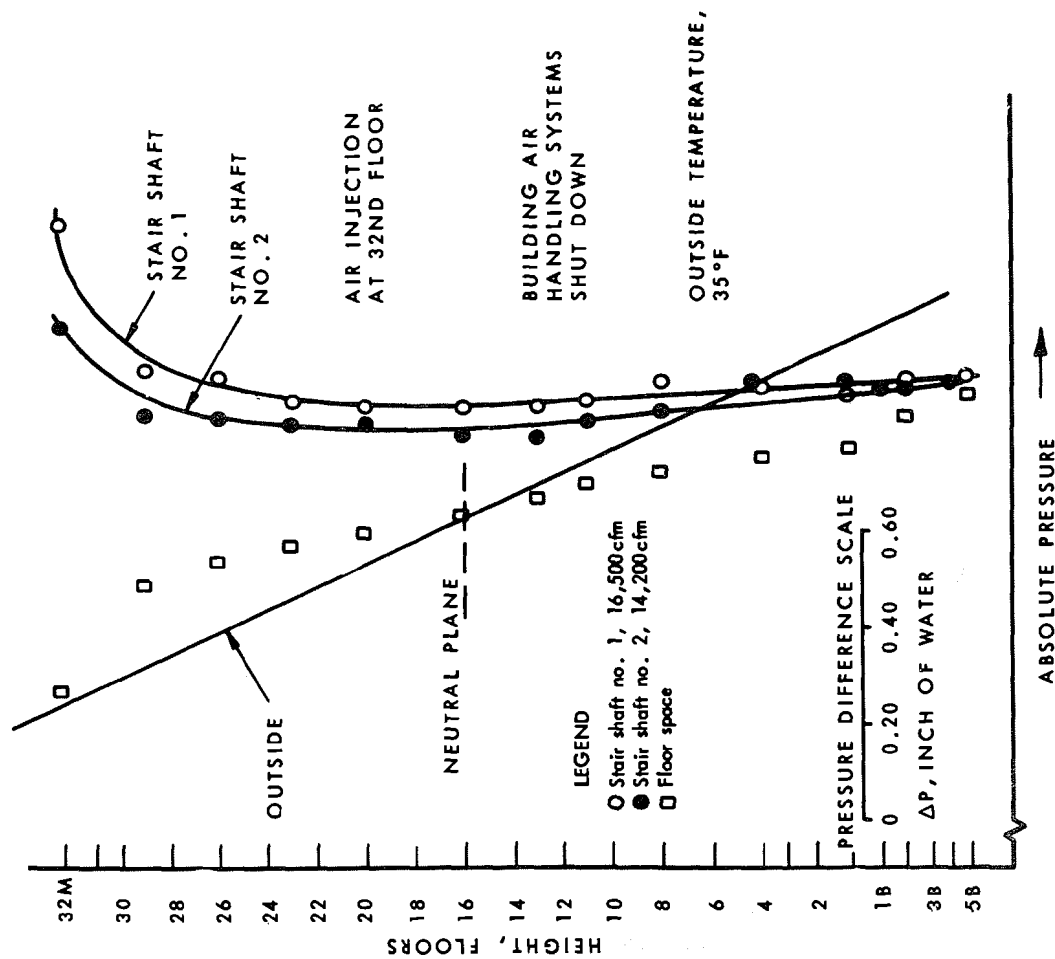


Fig. 7 Pressure characteristics with stair shafts pressurized, test No. B1 of building B

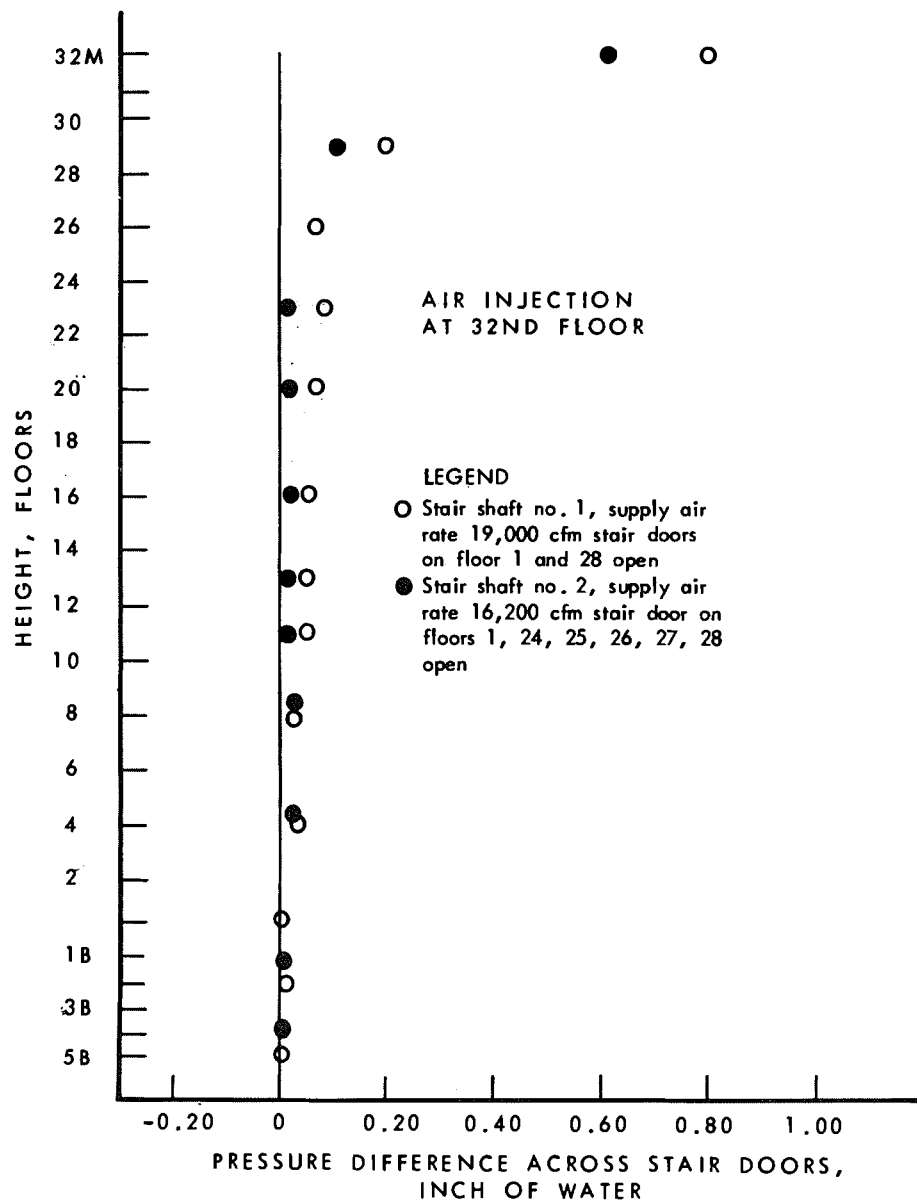


Fig. 9 Pressure differences across stair doors for test No. B3 of building B (open door tests)

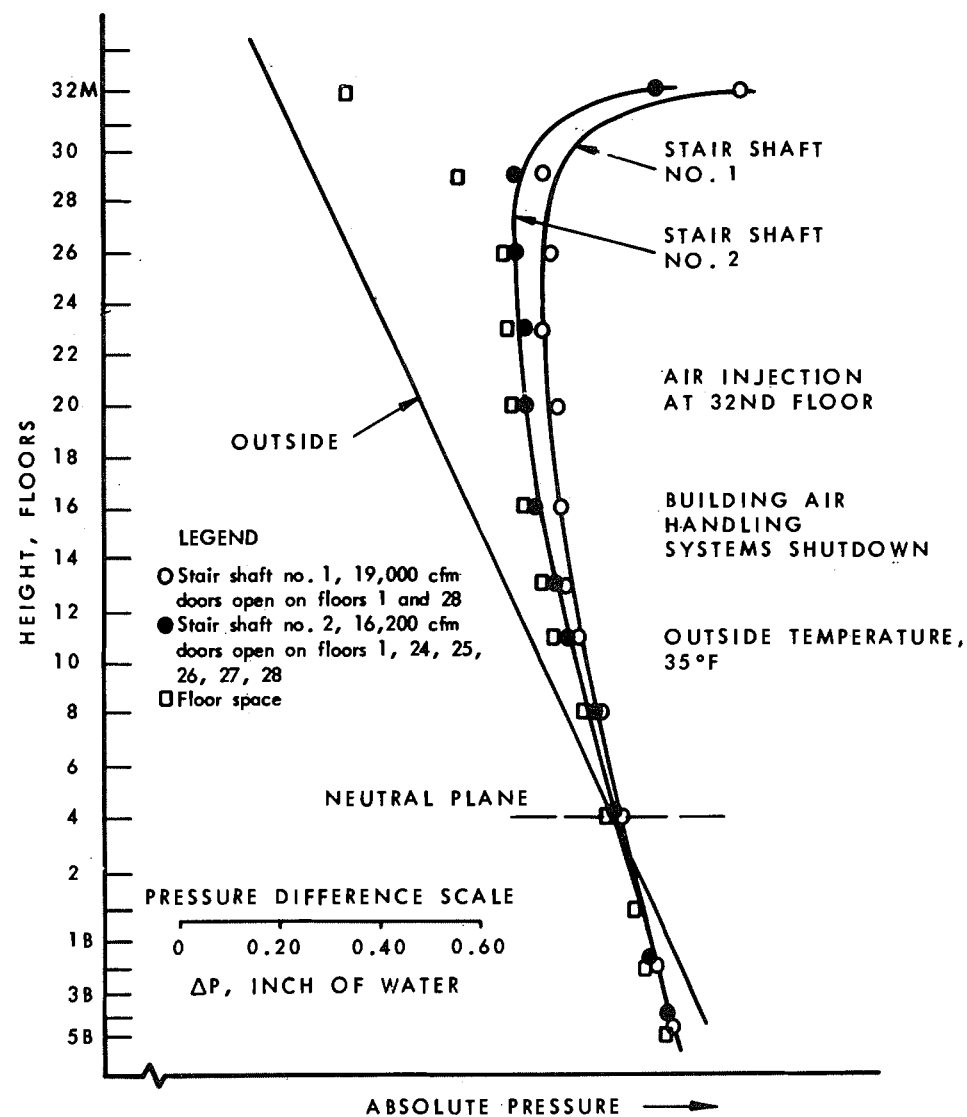


Fig. 10 Pressure characteristics with stair shafts pressurized and several stair doors open, test No. B3 of building B

DISCUSSION

MR. J.C. OLSEN (Tamblyn Mitchell & Partners, Toronto, Ontario, Canada): The slides indicated that the test was conducted in summer. Were any of the tests conducted at cold temperatures? If so what was the effect on stair pressurization with cold outside air? Do you anticipate a requirement to heat the air?

MR. TAMURA: Outside temperatures during stair pressurization tests were 50F with air injection at the bottom and 35F with air injection at the top. Measurements of air temperature inside the stair shaft indicated that these temperatures were close to that outside near the point of air injection but increased rapidly away from it until at a distance of about ten floors away, they approached the inside ambient air temperature as indicated in Fig. 4 and Fig. 8.

Injection of unheated outside air into the stair shaft during cold weather does not adversely affect the performance of a stair pressurization system. The requirement to heat the supply air, therefore, depends on whether or to what degree comfort condition should be provided for occupants evacuating through the stair shaft.

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