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FIELD TESTS OF STAIRSHAFT PRESSURIZATION SYSTEMS WITH OVERPRESSURE RELIEF*

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ABSTRACT

Three stairshaft pressurization systems with overpressure relief features have been tested in a twenty-two-story apartment building and in two high-rise office buildings. Specifically, exit door relief, barometric damper relief, and a feedback control with variable-pitch blade supply air fan were subjected to open-door tests. The pressure differences across the stair doors and air velocities at the stair door opening were measured.

Stairshafts in buildings must be maintained tenable during a fire, particularly in high-rise buildings where time to evacuate can be long and firefighting tends to be difficult. The stairshaft pressurization systems should prevent smoke infiltration during evacuation but the pressure maintained should not be so high as to make it difficult to open stair doors. To meet these requirements stairshaft pressurization systems usually require some means of overpressure control.

An ASHRAE research project was undertaken to develop and evaluate design procedures for such pressurization systems. Exit door relief, barometric damper relief, and feedback control of supply air for pressurization were selected for investigation. The first phase of the project involved review of the literature followed by tests in a ten-story experimental fire tower to determine flow coefficients at stair doors, and air velocities required to prevent smoke backflow at the stair door on the fire floor [1].

The second phase involved evaluation of stairshaft pressurization systems as installed, and identification of the test conditions requiring further investigation in

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the experimental fire tower. Tests were conducted on the stair pressurization systems with overpressure relief features of a twenty-three-story apartment building and two high-rise office buildings.

STAIRSHAFT PRESSURIZATION SYSTEMS WITH OVERPRESSURE RELIEF

There are two basic types of overpressure relief systems, one with constant-supply air rate and relief vents, and the other with variable-supply air rate and feedback control. The system with constant-supply air rate and an open exit door as relief vent is illustrated in Figure 1(a). The exit door opens to outside when the supply air fan is activated. This fan is sized for the specific case, i.e., exit stair door open and all other stair doors closed, so as to produce a pressure difference across the stair doors of at least 0.10 in of water (25 Pa) but no more than 0.40 in of water (100 Pa). The system is essentially the same as that recommended in the Supplement to the National Building Code of Canada, (1985) [2].

A variation on the above system is the use of barometric dampers as relief vents in the walls of the stairshaft (see Figure 1(b)). The supply air fan is sized to produce the required air velocity through open doors for the particular open stair door configuration and the barometric dampers are sized to prevent overpressurization when all stair doors are closed. A fire damper is placed in series with the barometric damper to maintain fire integrity of the stairshaft wall.

An exhaust duct with a relief damper or exhaust fan can also be used to prevent overpressurization of the stairshaft, but generally, it is not recommended owing to the possibility of negative pressures that could result in smoke contamination of the stairshaft. Such exhaust systems can be used, however, by firefighters for smoke-clearing operations.

A stairshaft pressurization system with variable supply air rate is illustrated in Figure 1(c). The supply air fan is sized to provide the required minimum air velocity through open stair doors for a particular open-door configuration, as for the previous case. The supply air rate is controlled to maintain a set pressure difference across the stair doors. This can be done by varying the speed of the fan or the pitch of a variable-pitch blade fan, or by operating the dampers of the fan bypass ductwork.

TEST BUILDINGS

Building A, a twenty-two-story apartment building, has two pressurized stairshafts with exit door reliefs. Each is equipped with a centrifugal fan having a capacity of 14 650 cfm (6.9 m^3/s) located on the roof. It supplies outside air to the stairshaft through supply air grilles 2 ft by 4 ft (0.61 m by 1.22 m) in the vertical air distribution shaft on floors 3, 9, 13, 18, and 22 (Figure 2). The exit door on the ground floor is 3.4 ft by 6.9 ft (1.0 m by 2.1 m) and opens automatically when the

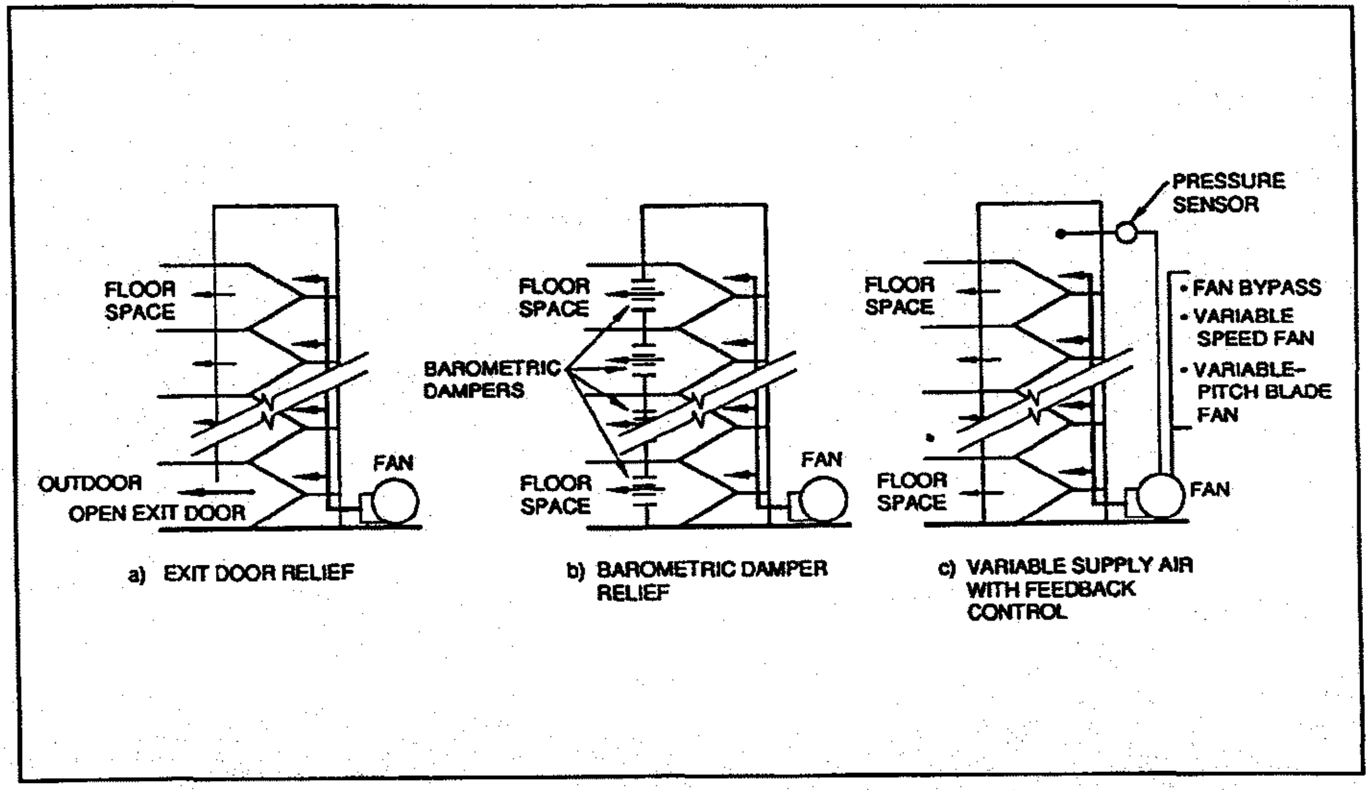

Figure 1. Overpressure relief systems.

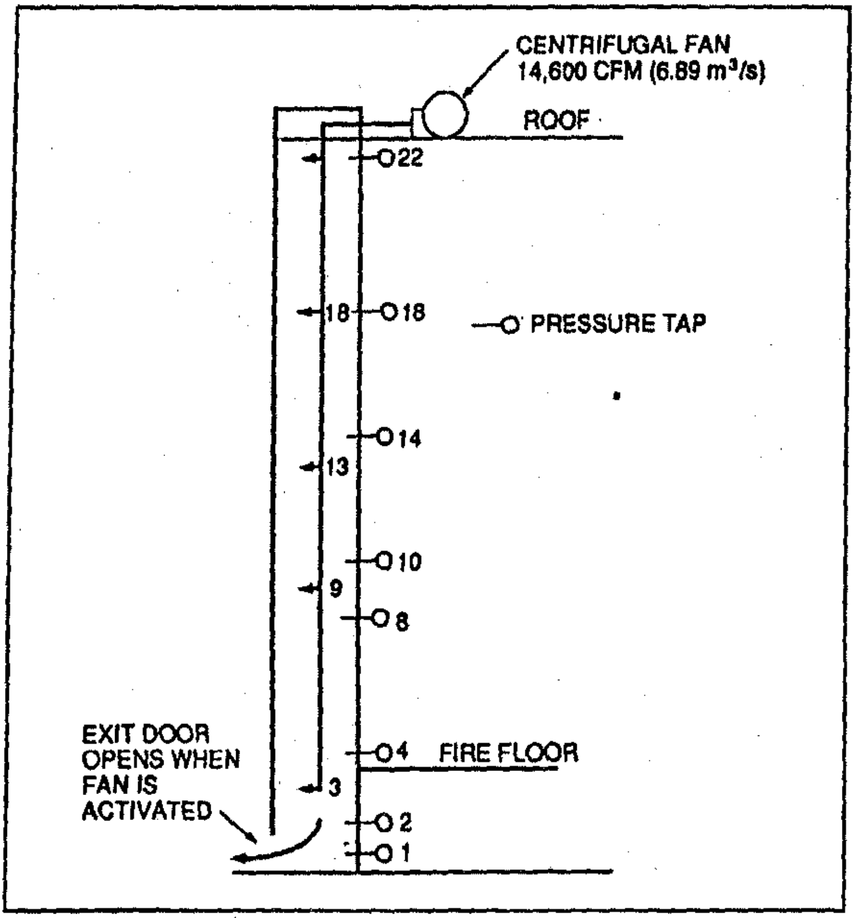

Figure 2. Test Building A (apartment)—exit door relief system.

supply air fan is activated. The size of each stair door is 3 ft by 7 ft (0.91 m by 2.1 m).

Building B, a thirty-nine-story office building, has a pressurized stairshaft with barometric damper reliefs and a smoke-proof stairshaft; these are vented lobbies located adjacent to the exterior wall. The pressurized stairshaft is equipped with two vane-axial fans located in the mechanical rooms on the first and thirty-ninth floors, each having a capacity of 20 000 cfm (9.44 m^3/s). The outlets from the fans are connected to the stairshaft to inject outside air directly into the stairshaft (Figure 3). Barometric dampers 1.33 ft by 3.50 ft (0.41 m by 1.07 m) are placed in a metal duct in the stairshaft wall above the stair door on floors 3, 5, 6, 36, and 37.

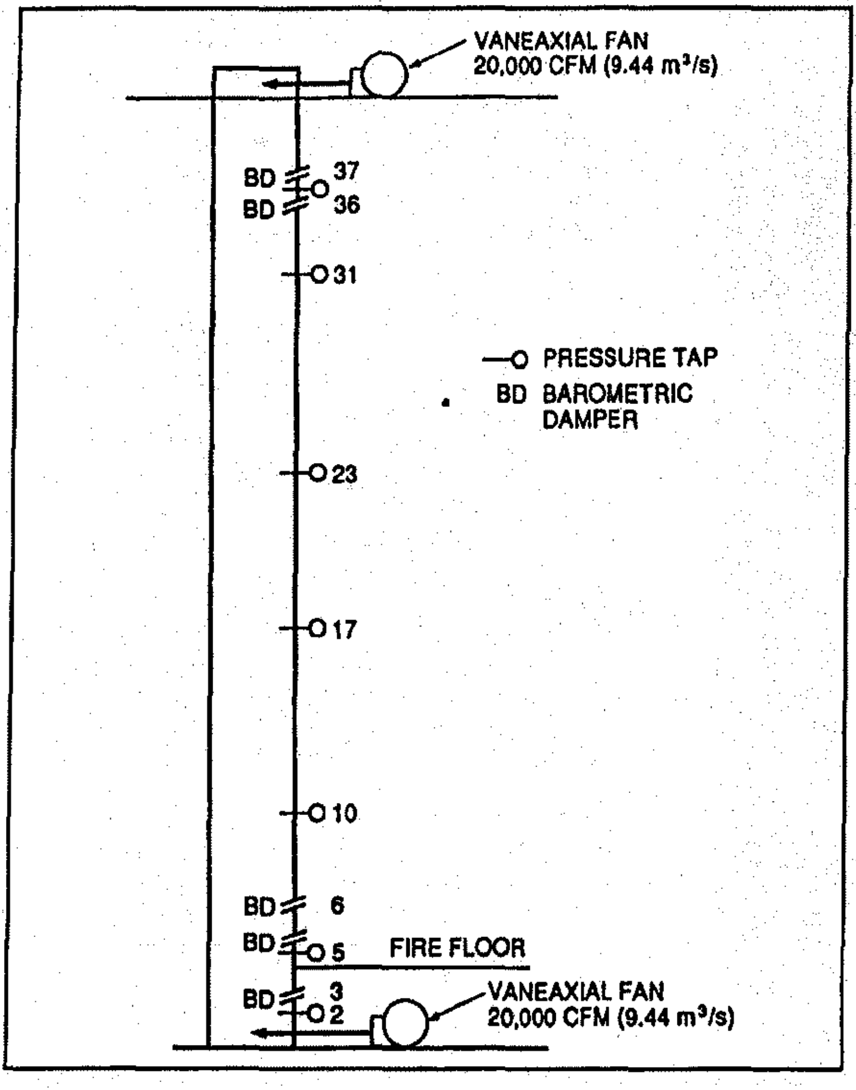

Figure 3. Test Building B (office)—barometric damper relief system.

A fire damper is placed in series with the barometric damper inside the metal duct, which opens to the false ceiling space on the floor side. The stair door is 3.7 ft by 7 ft (1.12 m by 2.1 m).

Building C, a forty-two-story office building, has two pressurized stairshafts each with a variable supply air system equipped with feedback control. Two vane-axial fans with variable-pitch blades are located on the first basement floor and on the forty-second floor, each having a capacity of 41 000 cfm (19.35 m3/s). The outlets for the two fans are connected to a common vertical air distribution shaft with supply air grilles of 1.5 ft by 5 ft (0.46 m by 1.52 m) opening to the stairshaft on every third floor, floors 3 to 39. The static pressure sensor and controller are located in the equipment room on the thirty-second floor, one side connected to the stairshaft and the reference side to the roof top. Its output controls the blade pitch of the two supply air fans. The size of the stair door is 3 ft by 9 ft (0.91 m by 2.7 m).

TEST PROCEDURE

There are many possible open door combinations for testing the stairshaft pressurization. It is almost impossible to design a practical stair pressurization system to operate properly when many or all stair doors are open. Stair doors will probably be open for prolonged periods on the fire floor for firefighting and on the exit floor for evacuation. As well, the stair door on the floor below the fire floor, often used as a staging area by firefighters, may be opened frequently for the duration of the fire. Tests were therefore conducted for progressive opening of stair doors on the fire floor, the exit floor, the floor below the fire floor, and on one of the upper floors, simulating evacuation from one of the upper floors. Although the angle of door opening can vary with door use during evacuation, tests were conducted with the stair doors in the full-open position as an extreme case. Because fire in a lower floor is likely to present the greatest risk to the building population, one of the lower floors was selected as the fire floor.

Pressure differences across the stair doors on several floors were measured with magnetic reluctance pressure transducers (stair shaft side—floor space side). Air velocity traverses were also conducted with a hot-wire anemometer at the stair door opening on the fire floor. The locations of the selected fire floor and floors on which the pressure differences across the stair doors was measured are shown in Figures 2, 3, and 4 for Buildings A, B, and C, respectively. The supply air rates for stairshaft pressurization during the tests were not recorded owing to difficulties with flow measurements during field tests. Tests were conducted with the stairshaft pressurization system off and all stair doors closed, followed by the main test with the stairshaft pressurization system on and various combinations of stair doors fully open. Also, they were conducted with no fire, with the building air-handling systems shut down, and with neither mechanical venting nor exterior wall venting of the assigned fire floor. The procedures followed for each building were essentially the same, with only minor variations depending upon the characteristics of the stairshaft pressurization systems.

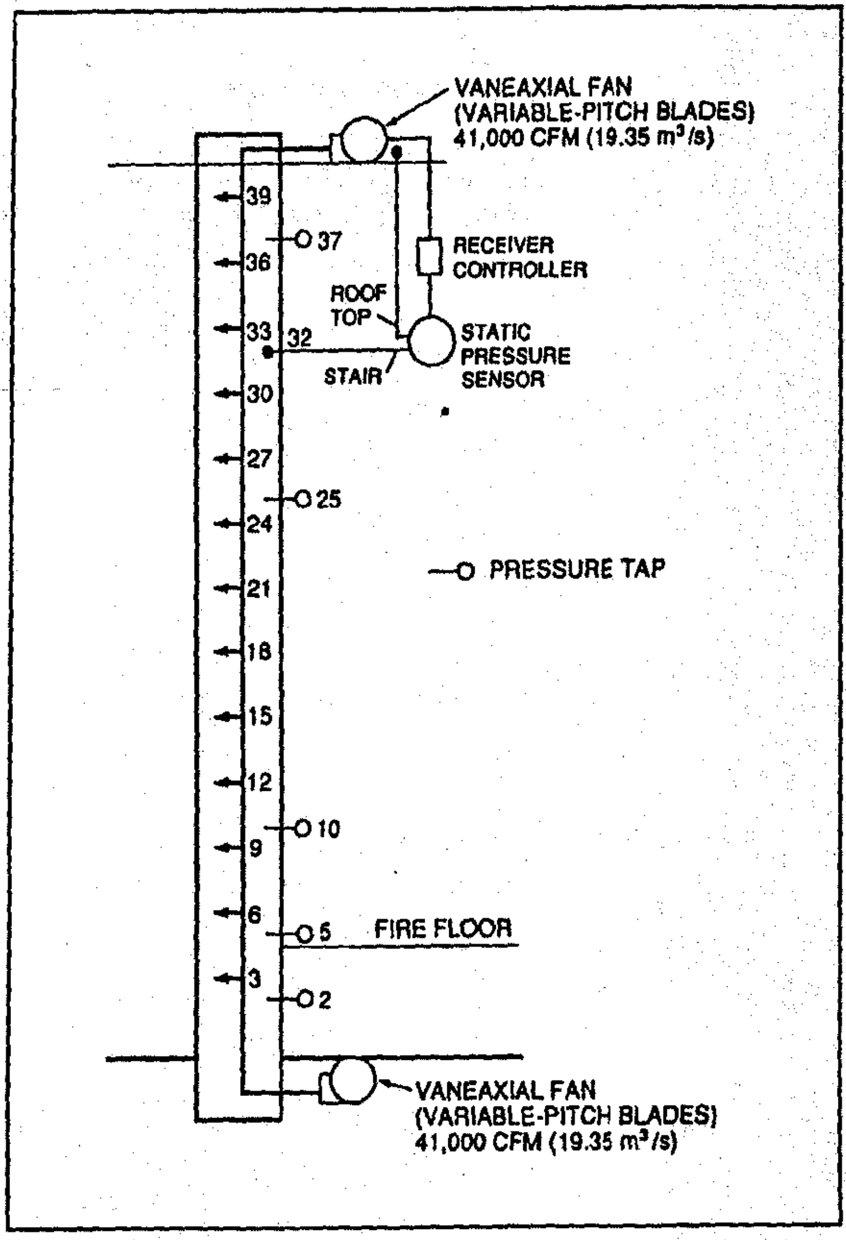

Figure 4. Test building (office)—variable supply air system with feedback control.

TEST RESULTS

Building A—Exit Door Relief

Pressure differences across the stair doors on floors 1, 2, 4, 8, 10, 14, 18, and 22 measured during the tests are shown in Figure 5. With all stair doors closed, except for the exit door on the ground floor (first floor) that opened automatically

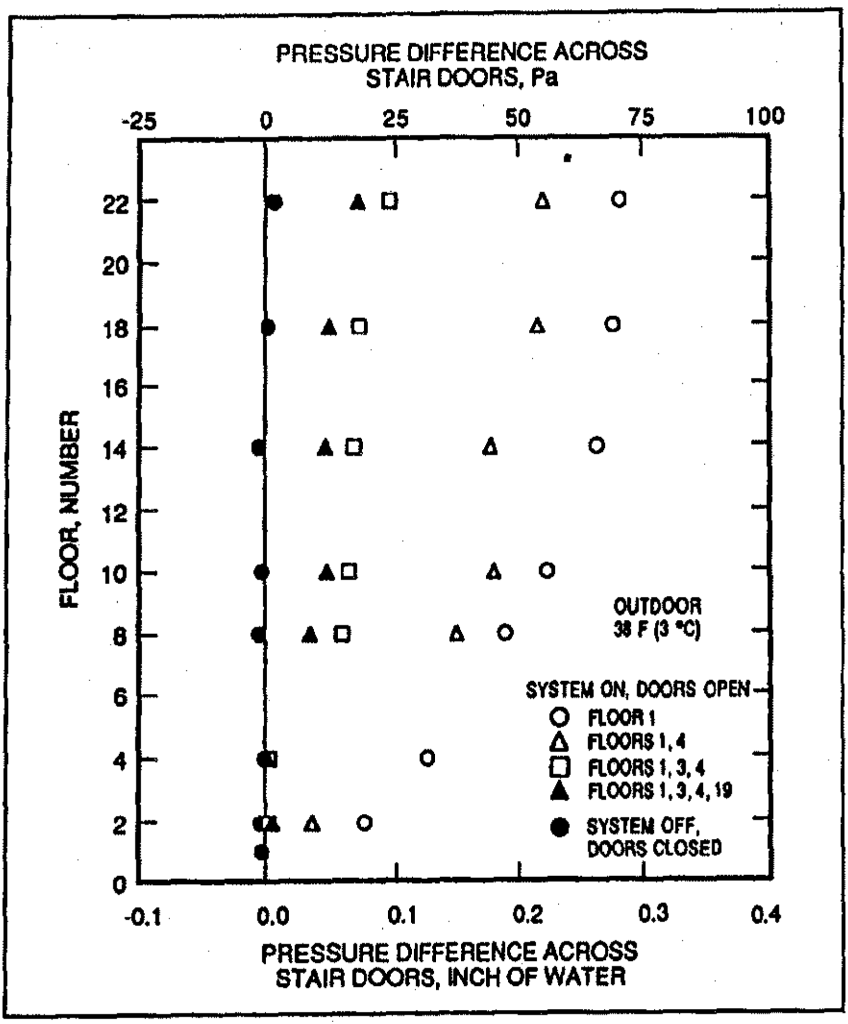

Figure 5. Pressure difference measurements of stairshaft pressurization system with exit door relief—Building A.

Table 1. Average Air Velocity at Stair Door Opening on the Assigned Fire Floor.

Test Building A—Exit Door Relief

Open Door, Floor	*Average Velocity, fpm (m/s) Fourth Floor*
1, [4]	132 (0.67)
1, [4], 3	134 (0.68)
1, [4], 3, 19	73 (0.37)
1, [4], 3, 19, 15	85 (0.48)

Test Building B—Barometric Dampers

	Average Velocity, fpm (m/s)	
Open Door, Floor	*Fifth Floor*	*Fourth Floor*
[5]	530 (2.70)	—
[5], 1	290 (1.49)	—
[5], 1, 4	88 (0.45)	319 (1.62)
[5], 1, 4, 35	61 (0.31)	280 (1.42)

	Damper Open, Floor				
Open Door, Floor	*3*	*5*	*6*	*36*	*37*
—	full	full	1/4	1/2	1/2
[5]	1/4	0	0	1/2	1/2
[5], 1	0	0	0	1/2	1/2
[5], 1, 4	0	0	0	1/2	1/2
[5], 1, 4, 35	0	0	0	1/4	1/2

Test Building C—Feedback Control—Variable-Pitch Blade Fan

Open Door, 90°, Floor	*Average Velocity, fpm (m/s), Fifth Floor*
[5]	210 (1.06)
[5], 1	200 (1.00)
[5], 1, 4	147 (0.75)
[5], 1, 4, 38	180 (0.91)

Note: [ ] = Assigned fire floor.

when the stairshaft pressurization was activated, the pressure differences across the stair doors were least on the second floor at 0.075 in of water (18.6 Pa) and greatest on the twenty-second floor at 0.28 in of water (70 Pa). The pressure differences subsequently decreased when the stair doors were opened sequentially. When the stair door on the fourth floor (assigned fire floor) was open, the pressure differences decreased, but they were above 0.10 in of water (25 Pa) except for the stair doors on the second and fourth floors. When, in addition, the third floor stair door was opened, the pressure differences decreased sharply, with values above the fourth floor between 0.05 in of water (12.5 Pa) and 0.10 in of water (25 Pa). When the stair door of the nineteenth floor was opened as well, there was a further decrease in the pressure differences. For all tests with the stair door open on the fourth floor (assigned fire floor), the pressure difference across the doorway on the fourth floor was about 0.003 in of water (0.7 Pa).

The average air velocities at the stair door opening on the fourth floor are given in Table 1. With the exit door open to outside, the average air velocity was 132 fpm (0.67 m/s); it was about the same when the stair door on the third floor was also opened. When, in addition, the stair door on the nineteenth floor was opened, the average air velocity was reduced by nearly one-half; it remained relatively unchanged when the stair door on the fifteenth floor was opened as well. Air flowed from the stairshaft to the floor space for all tests.

The outside temperature at the time of the test was 38 F (3°C). With the pressurization system off, the pressure difference across the stair door at the first floor leading to the corridor and the main lobby was 0.003 in of water (0.7 Pa), whereas the pressure difference across the stair door on the same floor, opening directly to outside, was 0.16 in of water (40 Pa). With the latter door open and with the fan operating, stack action probably assisted the pressurization system in holding pressures in the stairshaft.

Building B—Barometric Dampers

Pressure differences across the stair doors on floors 2, 5, 10, 17, 23, 31, and 37 measured during the tests are shown in Figure 6. With stairshaft pressurization off, the pressure difference readings indicated flow of air from the floor space to the stairshaft from the ground floor up to about the thirty-second floor and from the stairshaft to the floor space from there up. This airflow pattern was probably caused by stack action with outside air temperature of 45°F (7°C).

With the stairshaft pressurization system on and with all stair doors closed, the pressure differences varied from 0.23 in of water (57 Pa) to 0.34 in of water (85 Pa). When the stair door on the fifth floor (assigned fire floor) was opened, the pressure differences above the twentieth floor were between 0.10 in of water (25 Pa) and 0.20 in of water (50 Pa); below this floor (i.e., the 20th) they were between 0.05 in of water (12.5 Pa) and 0.10 in of water (25 Pa), except across the stair door opening on the fifth floor which had a value of 0.024 in of water (6 Pa). When the exit door opening to the main floor (first floor) lobby was also opened and when both stair doors on the first and the fourth floors as well the pressure differences were all above 0.05 in of water (12.5 Pa) except at the fifth and tenth floors. This was also the

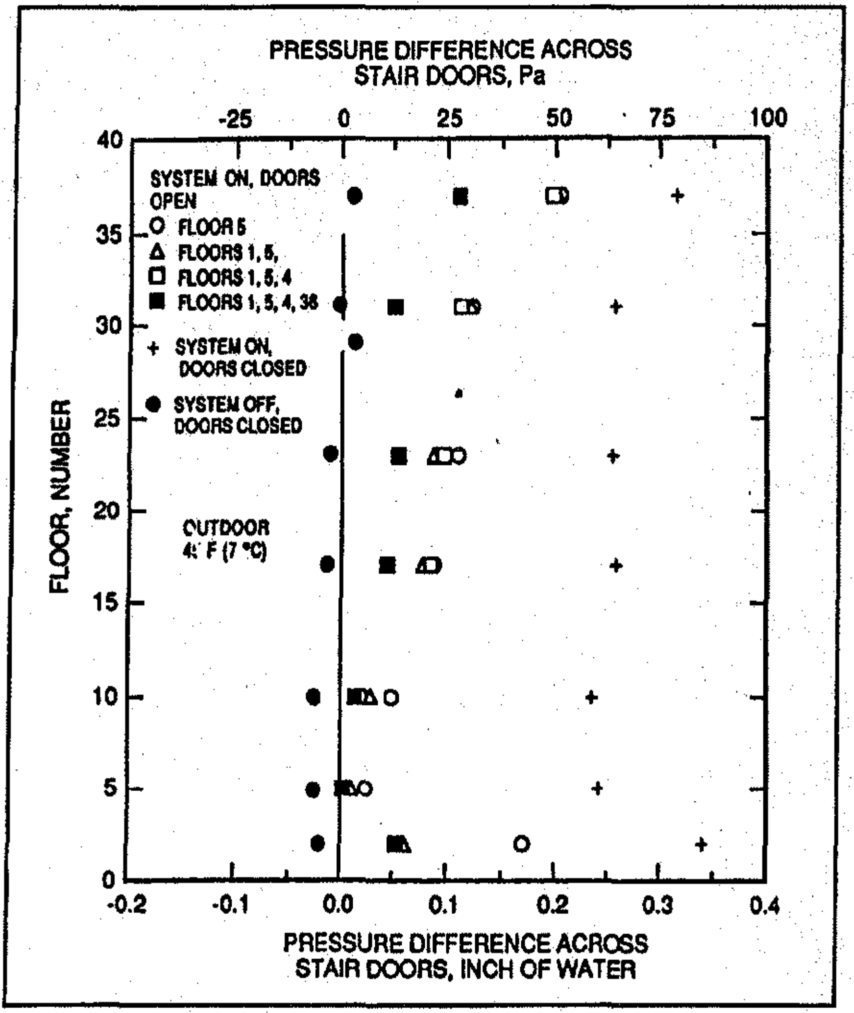

Figure 6. Pressure difference measurements of stairshaft pressurization system with barometric dampers—Building B.

case when in addition the stair door on the thirty-fifth floor was also opened, except at the seventeenth floor where the pressure difference was 0.044 in of water (11 Pa). Pressure differences across the open stair door at the fifth floor were 0.011, 0.001, 0.002 in of water (3, 0.5, and 0.5 Pa) when stair doors were open on floors 1 and 5, floors 1, 4, and 5, and floors 1, 4, 5, and 35, respectively.

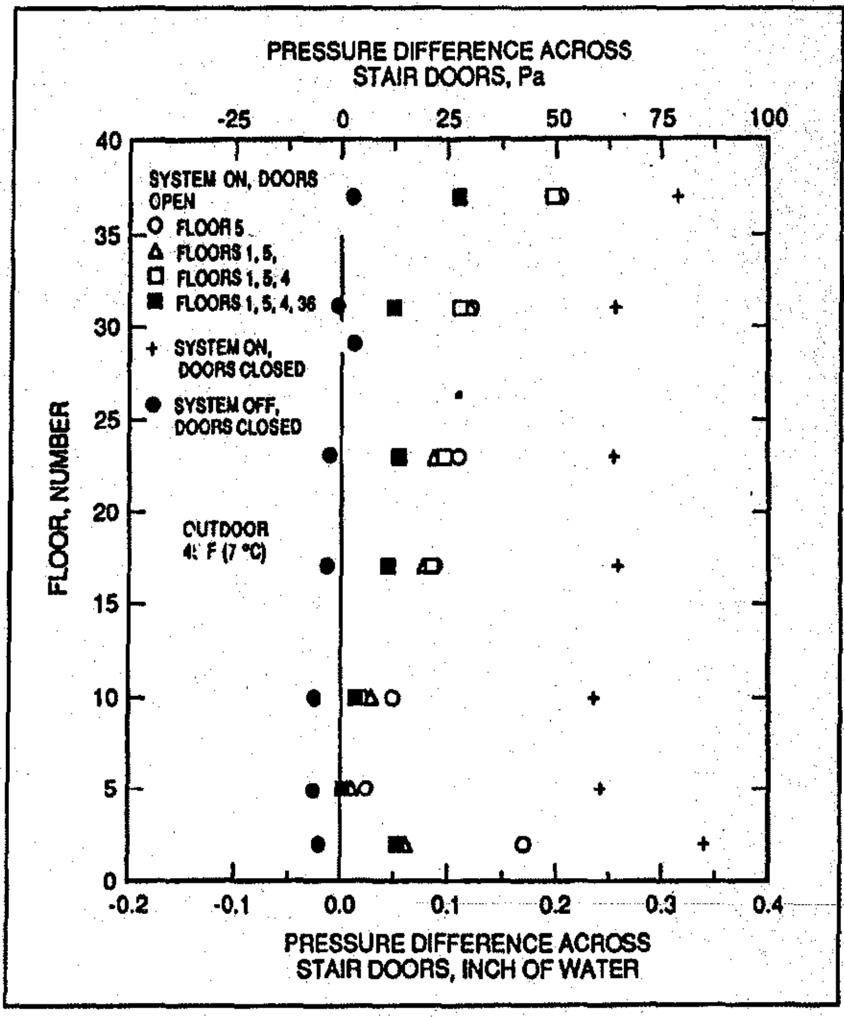

Figure 6. Pressure difference measurements of stairshaft pressurization system with barometric dampers—Building B.

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Average velocities at the stair door opening on the fifth floor are given in Table 1: 530 fpm (2.70 m/s) with no other door open and 290 fpm (1.49 m/s) with the first floor door open as well. When the stair door on the fourth floor was opened, the average air velocities reduced to 88 fpm (0.45 m/s). The corresponding average air velocity at the stair door opening at the fourth floor was 319 fpm (1.62 m/s); the much greater air velocity on this floor was probably due to its proximity to the point of injection of supply air on the first floor (Figure 3). When the stair door on the thirty-fifth floor was also opened, the average air velocity at the fifth floor doorway was 61 fpm (0.31 m/s) and at the fourth floor doorway 280 fpm (1.42 m/s). Injection points in addition to those at the top and bottom of the stairshaft could have reduced the differences in the air velocities on both floors.

The position of the barometric dampers during the tests are given in Table 1. They were located on floors near the points of air injection; at low levels on floors 3, 5, and 6, and at upper levels on floors 36 and 37. When the fifth floor stair door was opened, the dampers on the fifth and sixth floors closed and that on the third floor moved to the quarter-open position. As may be seen in Figure 6, there was a large reduction in pressure differences across the stair doors, i.e., about 0.15 in of water (37 Pa), in spite of the closing of the dampers. Closing the dampers probably helped to prevent greater reduction. When the stair door on the ground floor (1st floor) was also opened, the damper on the third floor closed. Dampers on the thirty-sixth and thirty-seventh floors remained open when the stair doors on floors 1, 4, and 5 were opened. When the stair door on the thirty-fifth floor was opened, the damper on the thirty-sixth floor moved from a half-open position to a quarter-open position, and that on the thirty-seventh floor remained in the half-open position.

Building C—Feedback Control (Variable-Pitch Blade Fan)

The first series of tests was conducted with the reference pressure tap of the static pressure controller (normally located on the roof) moved to the thirty-second floor away from the influence of wind pressures. Pressure differences across the stair doors on floors 2, 5, 10, 25, and 37 measured during the tests are shown in Figure 7. Because of rapid oscillation of the readings (which occurred most of the time), only average values are given. The cause of the oscillation was not determined; it could have been due to hunting of the static pressure controller or to the operating points to the left of the peak of the combined performance curve, where it is relatively flat for the two fans operating in parallel [3]. Because of oscillation in the pressure readings, the response time of the stair pressurization after each door operation could not be determined accurately.

With the system on and all stair doors closed, the pressure differences at the upper floors were above 0.15 in of water (37 Pa); at the lower floors they were

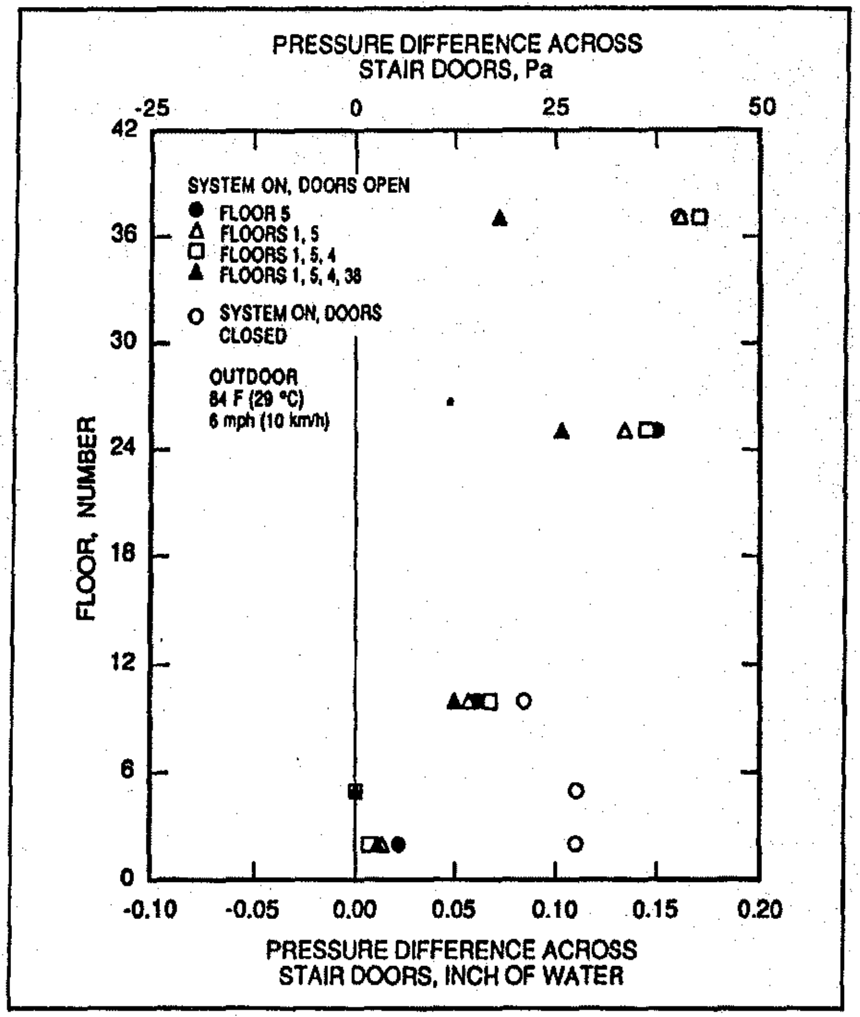

Figure 7. Pressure difference measurements of stairshaft pressurization system with feedback control (reference pressure for the controller on the thirty-second floor)—Building C.

0.085 in of water (21 Pa) on the tenth floor and 0.11 in of water (27 Pa) on the second. When the stair door on the fifth floor (assigned fire floor) was opened, the pressure differences on the upper floors remained essentially unchanged, but on the lower floors they decreased to 0.06 in of water (15 Pa) on the tenth floor and to 0.022 in of water (5 Pa) on the second floor. When the stair door on the first floor (leading to the ground floor lobby) was opened and when the stair doors on the first and fourth floors were opened the same pattern followed; pressure differences on the tenth floor remained above 0.05 in of water (12 Pa) but those on the second floor decreased further to 0.008 in of water (2 Pa). When the stair door on the thirty-eighth floor was opened the pressure differences on the twenty-fifth

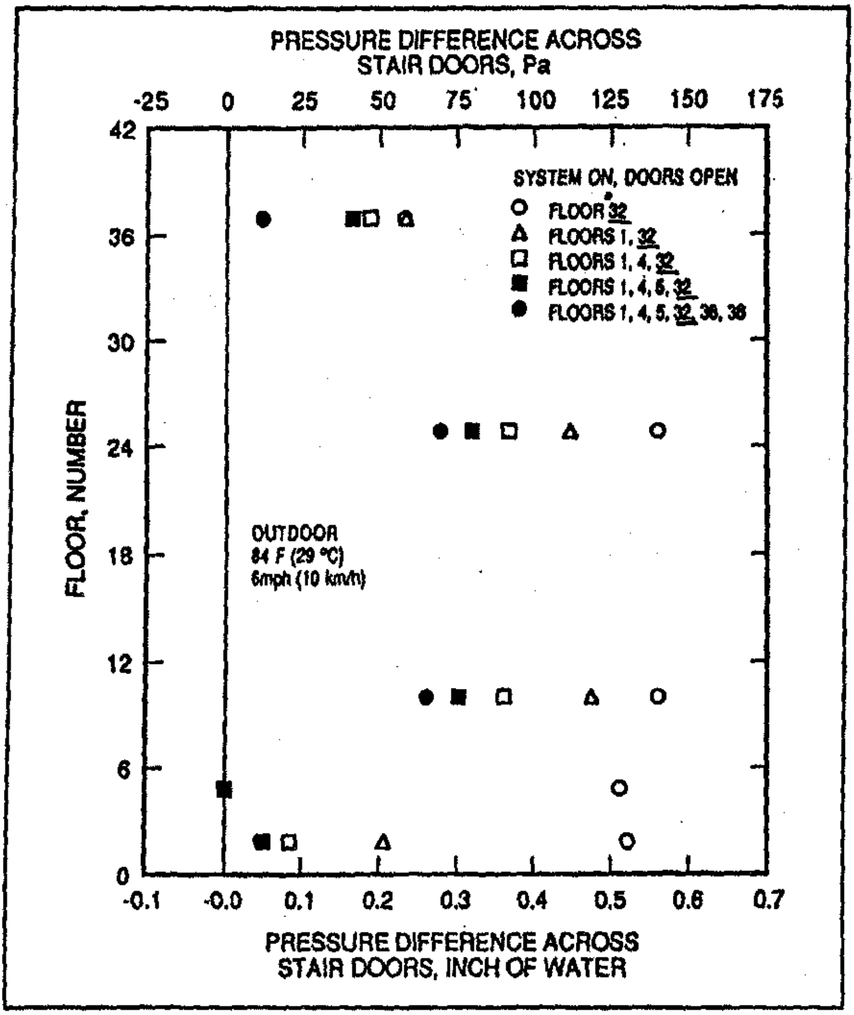

Figure 8. Pressure difference measurements of stairshaft pressurization system with feedback control (reference pressure for the controller on the thirty-second floor; stair door on this floor open)—Building C.

and thirty-seventh floors decreased to 0.10 in of water (25 Pa) and 0.07 in of water (17 Pa), respectively.

The average air velocities at the stair door opening on the fifth floor are given in Table 1. They were determined by using a 9-point hot-wire anemometer traverse instead of the 21-point traverse used in Buildings A and B. Building C was tested first, before the time of calibration of the hot-wire anemometer traverse during the

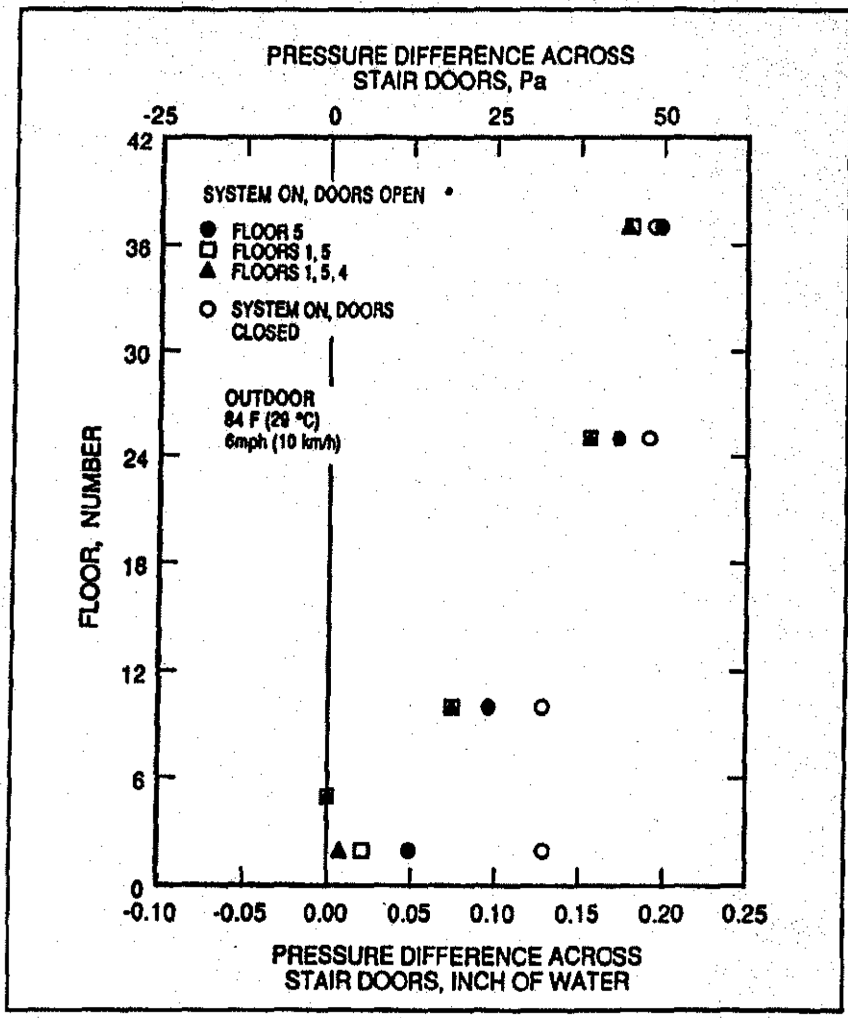

Figure 9. Pressure difference measurements of stairshaft pressurization system with feedback control (reference pressure for the controller on the roof top)—Building C.

first phase of this project [1]. Calibration of the traverse at an opening of a standard size door in the experimental fire tower during Phase 1 indicated that the 9-point traverse overestimates the average velocity by about 20 percent, whereas, the 21-point traverse gives a good estimate. The average velocity readings given in Table 1 for Building C were obtained, therefore, by reducing the 9-point traverse readings accordingly. With only the fifth floor stair door open, the average air velocity was 210 fpm (1.06 m/s). When, in addition, the stair door on the first floor was opened, it was 200 fpm (1 m/s) and with the stair door on the fourth floor also open it reduced to 147 fpm (0.75 m/s). When the stair door on the thirty-eighth floor was opened, the average air velocity on the fifth floor was about the same. In general, the average air velocity at the stair door opening on the fifth floor remained fairly constant during the door opening tests.

When the stair door on the thirty-second floor (where the reference pressure tap for the static pressure was relocated) was opened, pressure differences across the stair doors on floors 2, 10, and 25 increased to just above 0.50 in of water (125 Pa), as shown in Figure 8. As expected, the stair doors were difficult to open. The pressure differences decreased to below 0.40 in of water (100 Pa) when two more doors were opened.

A third series of tests was conducted with the reference pressure tap of the static pressure controller in its usual position on the roof top. The pattern of measured pressure differences for the door opening tests, as shown in Figure 9, were essentially the same, but with somewhat greater values than for the tests with the reference pressure tap located on the thirty-second floor (Figure 7). The operation of the controller with the reference pressure tap located at the roof top may be adversely affected during periods of high wind. This aspect could not be investigated at the time of the test as the wind speed was only 6 mph (10 kmh); the outside temperature was 84°F (20°F).

DISCUSSION

In Building A, the pressure differences across the stair doors with only the exit door open were 0.075 to 0.28 in of water (18 to 70 Pa). In Building B, the pressure differences across the stair doors, all stair doors closed, were 0.24 to 0.34 in of water (60 to 85 Pa); and in Building C, all stair doors closed, they were 0.13 to 0.19 in of water (32 to 47 Pa). The maximum pressure differences for stairshaft pressurization systems with overpressure relief features were well below 0.40 in of water (100 Pa) in the three buildings and unlikely to cause difficulties in opening stair doors.

Klote and Fothergill suggested a minimum pressure difference of 0.08 to 0.10 in of water (20 to 25 Pa) for a stairshaft directly exposed to fire, 0.06 to 0.08 in of water (15 to 20 Pa) for a stairshaft exposed to a remote fire, and 0.02 to 0.04 in of water (5 to 10 Pa) for a stairshaft exposed to a sprinklered fire [4]. These criteria, generally, were met by the stairshaft pressurization systems of the test buildings when three stair doors were open. In Building A (an apartment building) with stair doors open on floors 1, 3, and 4, pressure differences across the closed stair doors were above 0.06 in of water (15 Pa) except for the second floor where there was a pressure difference of 0.003 in of water (0.7 Pa). In Building B (an office building) with stair doors open on floors 1, 4, and 5, pressure differences were above 0.08 in of water (20 Pa) except for 0.018 in of water (4.5 Pa) on the tenth floor and 0.05 in of water (12.5 Pa) on the second floor. In Building C (an office building with a sprinkler system) with stair doors open on the same floors as for Building B, the pressure differences were above 0.02 in of water (5 Pa), except for 0.008 in of water (2 Pa) on the second floor.

The average air velocities at the stair doors opening on the assigned fire floors for Buildings A, B, and C were all greater than 50 fpm (0.25 m/s) with four stair doors open. Based on the papers by Shaw and Whyte [5] and Thomas [6], Klote and Fothergill [4] suggested that smoke backflow is prevented in a sprinklered building with air velocities between 50 and 250 fpm (0.25 to 1.25 m/s). According to Shaw and Whyte [5], 50 fpm (0.25 m/s) corresponds to a temperature difference between fire floor and stairshaft of 3.6°F (2°C). Australian Standard 1668, Part 1 requires an average air velocity of 200 fpm (1 m/s) [7]. Smoke backflow is prevented with this velocity at the open stair door for fire temperatures of 180°F (82°C) [1]. With two stair doors open, this criterion is met for Buildings B and C.

The installed supply air rates per floor for Buildings A, B, and C varied greatly, with values of 635 cfm (0.3 m^3/s), 1000 cfm (0.47 m^3/s), and 1950 cfm (0.93 m^3/s), respectively. The actual supply air rates during the tests were not measured. This will be done during the Phase 3 tests in the experimental fire tower to assist in determining the required supply air rates for stairshaft pressurization systems with various overpressure relief features.

The average air velocities at the stair door opening on the assigned fire floor would probably have been substantially greater with a large opening in the exterior walls, as would be caused by broken windows on the same floor. This aspect could not be checked in the test buildings, but will be investigated in the experimental fire tower during the third phase of the research project.

SUMMARY

Tests were conducted to check the performance of stairshafts with three different overpressure relief systems: exit door, barometric damper, and feedback control of a variable-pitch blade supply air fan. Each system was put through the same test schedule of stair door openings (three stair doors on the lower floors, including one designated as the fire floor and a stair door on one of the upper floors).

Pressure differences across the stair doors on several floors and air velocities at the stair door opening on the fire floor were measured. With all stair doors closed, the overpressure relief features of the stairshaft pressurization systems of all three buildings prevented overpressurization of the stairshaft. For three open stair doors, the pressure differences were generally above the applicable minimum values for the three test buildings. The average air velocities at the stair door opening on the assigned fire floor were greater than 50 fpm (0.25 m/s) with four stair doors open. In two of the test buildings, the average air velocities were about 200 fpm (1 m/s) with two stair doors open.

The field tests will be complemented by tests in the experimental fire tower when the performance of the systems under fire, winter, summer, and other operating conditions will be studied.

ACKNOWLEDGMENT

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