ASSESSMENT OF STAIR PRESSURIZATION SYSTEMS FOR SMOKE CONTROL

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ABSTRACT

An ASHRAE research project (RP-559) was undertaken to investigate the performance of various methods of overpressure relief for stair pressurization systems. The project consisted of four phases—a literature review of stair pressurization systems, field tests, fire tower tests, and computer model studies. The types of overpressure relief systems investigated were exit door relief, barometric damper relief, and feedback control, either with fan bypass, a variable-pitch blade fan, or a variable-speed fan. A related ASHRAE research project (RP-660) was conducted to determine the critical air velocities required to prevent smoke backflow at a stair door opening for various fire conditions. Using the results of these two research projects, this paper assesses the performance of stair pressurization systems and makes recommendations for their suitable application.

INTRODUCTION

Stairshafts, which are the principal means of escape during a building fire, must be maintained tenable while occupants are leaving the building. One means of preventing smoke from entering a stairshaft is by pressurizing the stairshaft with outside air using a supply air fan. Designing such a system to maintain a required level of pressurization is straightforward if all stair doors are assumed to be closed. However, during evacuation, stair doors are opened, resulting in intermittent losses of effective pressurization and allowing smoke to enter the stairshaft. On the other hand, supplying air in sufficient quantities to cope with open-door situations can result in overpressurization of the stairshaft when all doors are closed, thus making door opening difficult. To prevent such overpressure, stairshaft pressurization systems usually are designed with relief openings (exit door relief, barometric damper) or variable-supply air systems with feedback control (fan bypass, variable-pitch blade fan, variable-speed fan) (Figure 1).

To evaluate the effectiveness of stair pressurization systems with such overpressure relief features, an ASHRAE research project (RP-559) was undertaken. It consisted of determining test criteria and conducting field tests, tests in the experimental fire tower, and computer model studies. The results of these studies were reported in Tamura (1989; 1990a, b, c) except for the computer model studies, which are given in this paper. A related ASHRAE research project (RP-660) to determine the air velocities required to prevent smoke backflow at the open door of a pressurized stairshaft was also reported (Tamura 1991). This paper summarizes the results of those studies and delineates the limitations and capabilities of stair pressurization systems.

OUTLINE OF PROJECTS

Stair Pressurization Systems with Overpressure Relief (RP-559)

From a review of the literature (Phase 1) on stair pressurization systems, evacuation systems, and building

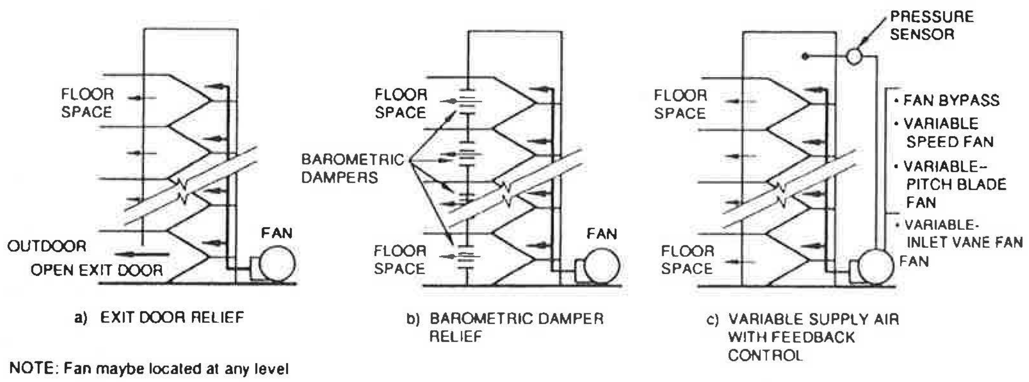

Figure 1 Overpressure relief systems.

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codes, a test schedule for stair door operation was established for use during the field tests (Phase 2) and fire tower tests (Phase 3).

Suitable test buildings were selected for the Phase 2 field tests. Nonfire tests were conducted on stair pressurization systems with three types of overpressure relief—exit door relief, barometric damper relief, and feedback control with a variable-pitch blade fan.

Phase 3 fire tests were conducted in a 10-story experimental fire tower (Figure 2) on stair pressurization systems with exit door relief, barometric damper relief, feedback control with fan bypass, and feedback control with a variable-speed fan. These stair pressurization systems were tested under both nonfire and fire conditions and under summer and winter conditions. They were tested alone and in combined operation with exterior venting and mechanical venting of the fire floor.

The studies in Phase 4 involved computer modeling of the stair pressurization systems using the computer program for calculating airflow networks and smoke concentration calculations (Yoshida et al. 1979; Said and MacDonald 1991). The computer model of the fire tower, which has only one experimental stairshaft, was used to simulate the operation of two stair pressurization systems under various fire configurations.

Air Velocities to Prevent Smoke Backflow (RP-660)

This research project involved determining the air velocities required to prevent smoke backflow at an open stair door on the fire floor of a pressurized stairshaft. Tests were conducted in the experimental fire tower for various fire temperatures, exterior wall vent openings, mechanical venting, and various open door angles. These tests were conducted to assist in evaluating the significance of the air velocities measured during Phases 2 and 3 of RP-559.

RESULTS AND DISCUSSION

Test Schedule

A literature review on stair pressurization systems, codes and standards, and evacuation studies was conducted. Little information was found in the literature on the performance of stair pressurization systems with overpressure relief features or on the use of stair doors during a fire.

There are many possible open-door combinations for testing stair pressurization systems. Some stair doors will probably be open for prolonged periods on the fire floor for firefighting and on the exit floor for evacuation. Also, the stair door on the floor below the fire floor, often used as a staging area by fire fighters, may be opened frequently during a fire.

From these considerations, the schedule selected for stair door operation was the 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. Although the angle of door opening can vary with door use during evacuation, the extreme case of a fully open stair door was specified. Since a fire on a lower floor is likely to present the greatest risk to the building population, one of the lower floors was designated as the fire floor.

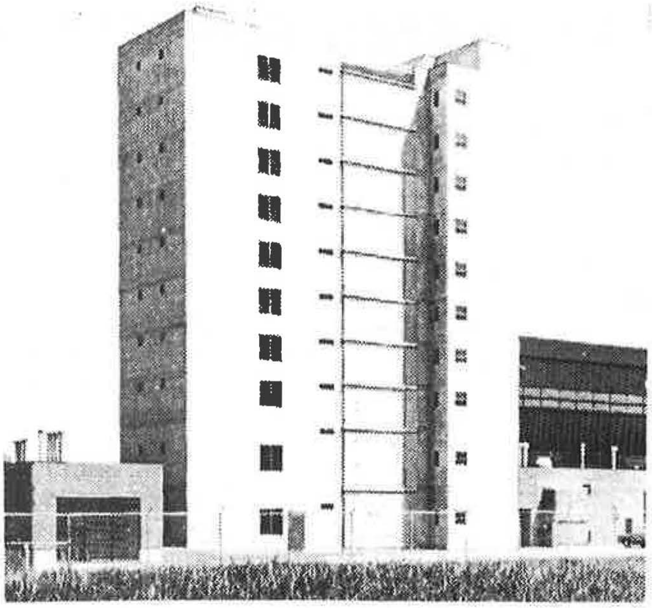

Figure 2 *Experimental fire tower.*

Test Criteria

The ASHRAE smoke control design manual (Klote and Fothergill 1983) suggests 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. For a ceiling height of 10 ft (3.05 m) and a neutral pressure level of approximately mid-height, the corresponding steady fire temperatures are as follows:

Pressure Difference (in. of water [Pa])	Fire Temperature (°F [°C])
0.02-0.04 [5-10]	280-770 [138-410]
0.05 [13.7]	1,400 [760]
0.055 [12.5]	2,000 [1,100]
0.06 [15.0] upper limit	> 2,000 [> 1,100]

Again according to the ASHRAE smoke control design manual (Klote and Fothergill 1983), smoke backflow is considered to be prevented in a sprinklered building with average air velocities of between 50 and 250 fpm (0.25 and 1.25 m/s). It also states that research is needed to fully evaluate the effect of sprinklers on smoke control design parameters. Australian Standard 1668, Part 1 (1979) requires an average air velocity of 200 fpm (1 m/s) with three stair doors open. The City of New York Local Law No. 84 (1979) requires an average air velocity of 400 fpm (2 m/s), also with three stair doors open.

The air velocities required to prevent smoke backflow at the stair door opening, obtained from tests in the experimental fire tower, are shown in Figure 3 (Tamura 1991). These are given for various fire temperatures with the fire floor vented either with exterior wall vents of 0, 10, 20, and 30 ft² (0.0, 0.93, 1.86, 2.79 m²) or with an exhaust fan. It can be seen in Figure 3 that the critical air velocities to overcome the fire pressures are much greater for the unvented cases than for the vented cases. From Figure 3, steady fire temperatures corresponding to the critical air velocities mentioned previously are as follows:

Critical Air Velocities (fpm [m/s])	Fire Temperature (°F [°C])
50-250 [0.25-1.25] ASHRAE	<4-360 [<2-182]
200 [1.0] Australia	250 [121]
400 [2.0] New York	900 [482]

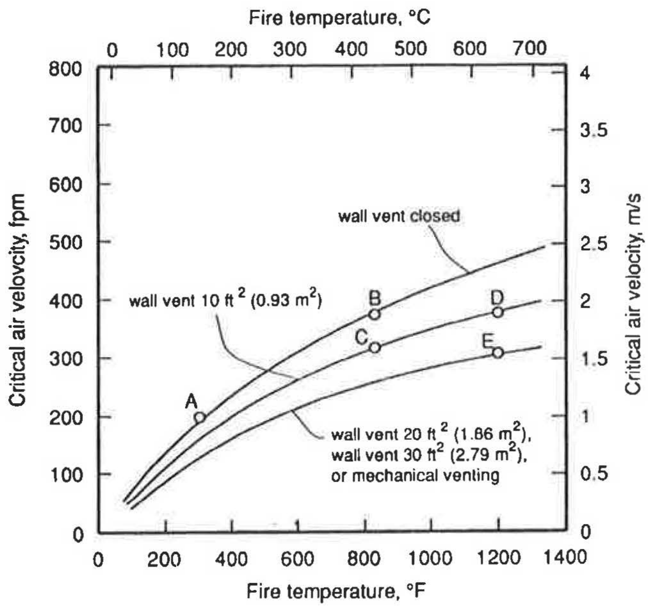

Figure 3 Critical air velocity vs. fire temperature.

Field Studies

Buildings having stair pressurization systems with overpressure relief were tested under the door-opening schedule. A stair pressurization system with exit door relief was tested in a 22-story apartment building, one with barometric damper relief was tested in a 39-story office building, and a third, with feedback control and a variable-pitch blade fan, was tested in a 42-story office building. The installed supply air rates per floor were 635 cfm (0.3 m³/s) for exit door relief, 1,000 cfm (0.47 m³/s) for barometric damper relief, and 1,950 cfm (0.92 m³/s) for the feedback control system. Pressure differences across stair doors on several floors were measured, and air velocity traverses were conducted at the stair door opening of the designated fire floor.

The results of the field tests were as follows:

- The overpressure relief features of the stair pressurization systems in all three buildings performed their function in preventing overpressurization of the stairshaft.
- Overpressurization of the stairshaft did occur, however, in the stair pressurization system with feedback control when the reference pressure tap located on the roof (for the static pressure controller) was moved to the floor space of the 32d floor to eliminate the effects of wind. When the stair door on that floor was opened, the pressure differences across the stair doors on other floors exceeded 0.50 in. of water (125 Pa). This is more than the pressure difference of 0.40 in. of water (100 Pa) across a standard-size door that can interfere with door operation. The pressure difference criterion of 0.02 in. of water (5 Pa) for a sprinklered fire was met by the stair pressurization systems in the test buildings when three stair doors were open.
- The average air velocities at the stair door opening on the assigned fire floor of each of the three test buildings, with three stair doors open, were less than the 200 fpm (1 m/s) required to prevent smoke backflow for a fire temperature of 250°F (121°C) as given in Figure 3 (Point A). They were 134 fpm (0.68 m/s), 88 fpm (0.45 m/s), and 147 fpm (0.75 m/s) for stair pressurization systems with exit door relief, barometric damper relief, and variable-supply air rate with feedback control, respectively. With two stair doors open, they were 132 fpm (0.67 m/s), 290 fpm (1.49 m/s), and 200 fpm (1 m/s), respectively.

Experimental Fire Tower Studies

The performance of the four stair pressurization systems was evaluated in a 10-story experimental fire tower in Canada under nonfire/fire and summer/winter conditions with the second floor used as the fire floor. The test fire temperatures were obtained with a 2.5-MW propane gas burner. Pressure differences across the walls of vertical shafts, air temperatures, and carbon dioxide concentrations inside the vertical shafts and floor spaces were measured. The smoke backflow conditions at the stair door opening on the fire floor were observed and recorded.

The stair pressurization systems that were investigated had overpressure relief provided by an exit door, a barometric damper, feedback control with fan bypass, and feedback control with a variable-speed fan. They are described in Table 1. For all pressurization systems, the supply air was injected into the stairshaft on floors 1, 3, 5, 7, and 10.

For the stair pressurization system with exit door relief with the exit stair door open to the outdoors, the stairshaft was pressurized to 0.10 in. of water (25 Pa) pressure difference across the stair door on the second floor with a supply air rate of 1,780 cfm (84 m³/s) per floor. For the stair pressurization system with barometric dampers in the walls of the stairshaft on each floor, with all stair doors closed, the stairshaft was pressurized to 0.40 in. of water (100 Pa) pressure difference across the stair doors with a supply air rate of 2,800 cfm (1.32 m³/s) per floor. For the two stair pressurization systems with feedback control, the pressure difference across the stair door on the fifth floor was set to 0.10 in. of water (25

TABLE 1
Description of Test Stair Pressurization Systems

	Pressure Difference in. of water (Pa)	Supply Air Rate per Floor cfm (m^3/s)
Exit Door Relief	0.10 (25)	1,780 (0.84)
Barometric Damper Relief	0.40 (100)	2,800 (1.32)
Feedback Control Fan Bypass, Variable-Speed Fan	0.10 (25) setpoint	3,300 (1.56) maximum
Note: Multiple injections on floors 1, 3, 5, 7, and 10 for all systems.		

Pa); the maximum supply air rate was approximately 3,300 cfm (1.56 m^3/s) per floor. These supply air rates (see Table 1) were all greater than those of the stair pressurization systems in the field.

Nonfire tests were conducted with stair doors opened in sequence on floors 2 (fire), 1, 3, and 8. Pressure and air velocity measurements were conducted first with the exterior wall vents on the second floor closed and then with them open. Fire tests were conducted at a temperature of 840°F (450°C) with exterior wall vents on the second floor closed (low-temperature fire) and at a temperature of 1,200°F (650°C) with the exterior wall vents (10 ft^2 [0.93 m^2]) open (high-temperature fire). The fire temperatures were measured just below the ceiling above the test gas burner. The stair doors were opened fully in the same sequence as for the nonfire tests until smoke backflow was observed at the stair door opening on the fire floor. The door on the fire floor was then closed gradually and the reduced door angle, which prevented smoke backflow, was noted.

Tests were conducted to investigate the effect of stack action in winter on the stair pressurization systems. Tests were also conducted to determine a suitable location for the reference pressure tap of the static pressure transmitter for the pressure control system and to determine the response times for the pressure control system used for the fan bypass and variable-speed fan pressurization systems.

The results of the tests were as follows:

- For the cases of two and three stair doors open, the air velocities at the stair door opening of the designated fire floor were lower than those measured in the field with the exterior wall vents closed, but they were greater with the exterior wall vents (10 ft^2 [0.93 m^2]) open. The supply air rates per floor were two to three times greater than those of the pressurization systems in the field.
- Under summer conditions, with neither exterior wall venting nor mechanical venting of the fire floor and with a fire temperature of 840°F (450°C), smoke backflow occurred for all stair pressurization systems when the stair door on the fire floor and the one on the exit floor were opened. The average air velocities at the stair door opening on the fire floor were from 106 to 130 fpm (0.54 to 0.66 m/s). The required air velocity from Figure 3 (Point B) is 370 fpm (1.85 m/s) at this fire temperature. Smoke backflow, which occurred in 35% to 40% of the upper area of the door opening, was prevented when the stair door was closed to a 10° open angle. The air velocity could have been increased by decreasing the door angle from the fully open position. It is increased by factors of about 1.2, 1.5, and 3.5 for open angles of 60°, 30°, and 10°, respectively.
- Under summer conditions, with a fire temperature of 840°F (450°C) and the exterior wall vents (10 ft^2 [0.93 m^2]) on the fire floor opened, smoke backflow occurred for all pressurization systems, except the one with barometric damper relief, when three stair doors were opened. The average air velocities at the stair door opening on the fire floor were from 238 fpm (1.28 m/s) to 254 fpm (1.29 m/s) for all stair pressurization systems, except for the one with barometric damper relief of 270 fpm (1.37 m/s). These were lower than the air velocity required to prevent smoke backflow (310 fpm [1.6 m/s]), as shown in Figure 3 (Point C). At a fire temperature of 1,200°F (650°C), smoke backflow occurred with two stair doors open with average air velocities ranging from 260 fpm (1.31 m/s) to 309 fpm (1.57 m/s). These were less than the critical air velocities at this fire temperature (360 fpm [1.80 m/s]), as shown in Figure 3 (Point D).
- Under winter conditions, when the exit stair door was open to the outdoors, stack action assisted the stair pressurization systems in maintaining pressures in the stairshaft. All pressurization systems performed better under winter conditions than under summer conditions.
- In preventing smoke backflow, the performance of the stair pressurization system with exit door relief was somewhat below that of the other pressurization systems investigated. The supply air rate for the former, however, was only about 65% of the latter.
- The response times of the two stair pressurization systems with feedback control were sufficiently long that, with a reduction in pressures caused by the opening of stair doors, momentary smoke contamination of the stairshaft could be expected until the stairshaft regained its setpoint pressure. For both the fan bypass and the variable-speed fan systems, there was a sharp drop in pressure difference when the first door was opened. With the feedback control opera-

ting, the supply air rate was increased so that the pressure difference rose to two-thirds of its initial reading in four minutes and returned to its initial reading in about ten minutes. Because of the lag in system response, when the last door was closed, a momentary pressure difference of 1.47 in. of water (365 Pa) for the fan bypass system and 0.73 in. of water (180 Pa) for the variable-speed fan system occurred inside the stairshaft and the supply air duct.

Overpressure in the stairshaft also occurred when the stair door on the floor with the reference pressure tap of the static pressure transmitter was opened, as was the case in the field test of a 42-story building. The overpressure was approximately 0.65 in. of water (162 Pa). The preferred location for the reference static pressure tap was found to be inside the service shaft that connects to all floor spaces rather than in one floor space or the roof, where it is exposed to wind pressures.

Mechanical Venting of the Fire Floor

Tests were conducted to assess the performance of the mechanical venting system in preventing smoke backflow into the stairshaft. The second floor was exhausted at a rate of 10,500 cfm (4.97 m^3/s) to produce a pressure difference of 0.10 in. of water (25 Pa) across the stair door on the second floor. The required exhaust rate for office buildings is about 6 air changes per hour (Tamura and Shaw 1978). This was followed by tests conducted with the mechanical venting system operated together with each of the four stair pressurization systems separately. The above tests were conducted for low- and high-temperature fires under summer conditions only. The results were as follows:

- Mechanical venting of the fire floor by itself prevented smoke contamination of the experimental fire tower, including the stairshaft. When the stair door on the fire floor was opened, smoke entered the elevator and service shafts and moved from there to upper floor spaces and into the stairshaft.
- With four stair doors open, the combined operation of mechanical venting with any one of the tested stair pressurization systems prevented smoke contamination of the stairshaft for the fire conditions investigated. Although the remainder of the tower was contaminated with smoke, the smoke concentrations were lower than in the case of stair pressurization systems without mechanical venting.
- The minimum average air velocity recorded at the open stair door during the nonfire tests for the four stair pressurization systems was 348 fpm (1.77 m/s), which was more than the critical air velocity of 300 fpm (1.5 m/s) for a fire temperature of 1,200°F (650°C) given in Figure 3 (Point E).

Computer Model Studies for Stair Pressurization System with Exit Door Relief

The cases for one pressurized stairshaft under summer conditions were run to determine their relationship with the results from the experimental tower. When the stair doors on the second (fire) floor and the ground floor were open, the stairshaft was contaminated with smoke in both the low- and high-temperature cases. This agreed with the experimental results.

The results of cases with two stairshafts pressurized are summarized in Table 2. When the door of one stairshaft on the second floor was opened, this stairshaft was contaminated, whereas the other stairshaft remained free of smoke for both the low- and high-temperature cases. When the doors of both stairshafts were opened on the second floor, both stairshafts were contaminated with smoke.

TABLE 2
Results of Computer Model Studies on the Stair Pressurization Systems with Exit Door Relief

	Two Stairshafts Pressurized	
	Stairshaft A	Stairshaft B
Stair A - Door open on fire floor	X	O
Stairs A and B - Doors open on fire floor	X	X
Mech. Venting Stair A - Door open on fire floor	O	O
Mech. Venting Stairs A and B - Doors open on fire floor	X	X

Note: X = smoke contamination; O = clear. Results apply to summer and both low- and high-temperature fire conditions.

Under the combined operation of stairshaft pressurization system and mechanical exhaust of the second floor, when the stair door of the one stairshaft was open on the second floor, both stairshafts remained clear of smoke in the low- and high-temperature cases. When the doors of both stairshafts were open on the second floor, however, both stairshafts were contaminated in the low- and high-temperature cases. Apparently, the flow of air from both stairshafts onto the second floor reduced the favorable pressure difference between the fire floor and the stairshaft sufficiently to be overcome by the fire pressures. This resulted in smoke backflow at the door openings of both stairshafts.

Air-Injection Method

Multiple injection of outside air was used for the four pressurization systems tested in the experimental fire tower. Additional tests were conducted to assess the effect of the methods of air injection on the stair pressurization system with exit door relief on the ground floor only. Figure 4 compares the pressure differences with top, multiple, and bottom injection at a total supply air rate of

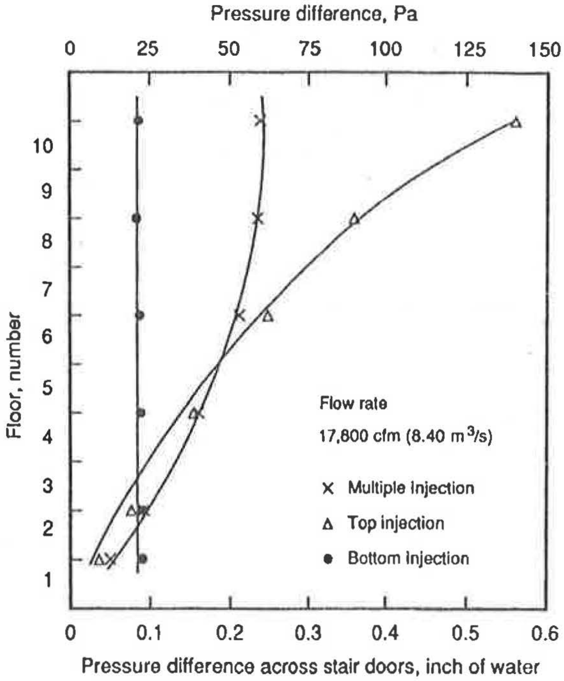

Figure 4 *Pressure difference measurements of stair pressurization system with exit door relief for top, bottom, and multiple injections.*

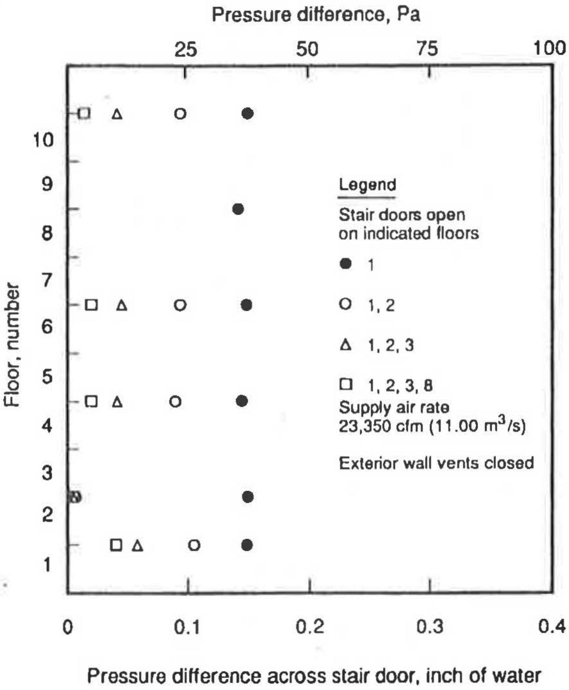

Figure 5 *Pressure difference measurements of stair pressurization system with exit door relief, nonfire condition, bottom injection.*

17,800 cfm (8.40 m^3/s) under nonfire conditions. For both the top- and multiple-injection methods, the pressure differences are greatest at the top floor and least at the bottom floor. On the other hand, the pressure differences with bottom injection are uniform from the top to the bottom of the stairshaft.

Figure 5 illustrates the effect of door operation with bottom injection, again for the nonfire condition. Except for the pressure differences on the floor where the door is open, the pressure differences are fairly uniform from the top to the bottom of the stairshaft. With bottom injection, more air can be injected (compared to top or multiple injection) without causing excessive pressure across the stair doors.

SUMMARY OF TESTS

- Tests in the field and in the experimental fire tower have indicated that, without venting the fire floor, smoke contamination of the stairshaft—with any of the test stair pressurization systems—can be expected when three or more stair doors are open. The average air velocities were less than the 200 fpm (1 m/s) required to prevent smoke backflow at an open stair door of the fire floor for a fire temperature of 250°F (121°C).
- Airflow through the open stair door caused the pressures on the fire floor to increase, resulting in smoke flow into elevator and service shafts and from there into upper floor spaces.
- Reducing the open-door angle significantly minimized the amount of smoke backflow and also reduced the rate of airflow into the fire floor.
- When the pressurization systems were operated in combination with mechanical venting of the fire floor, smoke backflow was prevented with four stair doors open. Computer model studies, however, indicated that smoke backflow can occur if stair doors of two pressurized stairshafts are wide open on the fire floor.

RECOMMENDATIONS

Tests have indicated that, in general, it is difficult to design a stair pressurization system that, by itself, can prevent smoke backflow at a stair door opening on the fire floor, even for a sprinklered fire.

- To safeguard the stairshaft from smoke contamination, the stair pressurization system should operate together with a mechanical exhaust fan to vent the fire floor. Also, the fire should be sprinklered to minimize the adverse pressures and smoke caused by fire, and to prevent window breakage, which could result in an increase in adverse pressures and smoke caused by fire from wind action and stack action caused by the differences in the inside and outside air temperatures.
- Lobbies associated with the stairshaft can be used to provide some control of door openings adversely affecting the pressures in the stairshaft. Also, the stairshaft can be separated into two or more compartments with doors between compartments to provide further control of stairshaft pressures. These approaches should be considered for tall office buildings where time for total evacuation can be

exceptionally long.

- The design of a stair pressurization system should be checked with a network airflow computer program, such as the one in the ASHRAE smoke control design manual, to see whether it meets the design intent considering type of occupancy, occupant density, building height, fire safety system, stair door operation, weather, and other factors.

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REFERENCES

Australian Standard 1668, Part 1. 1979. *SAA mechanical ventilation and air-conditioning code, part 1—Fire precautions in buildings with air-handling systems.* North Sydney, N.S.W.

City of New York. 1979. Local law no. 84.

Klote, J.H., and J.W. Fothergill, Jr. 1983. *Design of smoke control systems for buildings.* Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

Said, N.A., and R.A. MacDonald. 1991. An evaluation of a network smoke control model. *ASHRAE Transactions* 97(1).

Tamura, G.T. 1989. Stair pressurization systems for smoke control: Design considerations. *ASHRAE Transactions* 95(2): 184-192.

Tamura, G.T. 1990a. Field tests of stair pressurization systems with overpressure relief. *ASHRAE Transactions* 96(1): 951-958.

Tamura, G.T. 1990b. Fire tower tests of stair pressurization systems with overpressure relief. *ASHRAE Transactions* 96(2): 373-383.

Tamura, G.T. 1990c. Fire tower tests of stair pressurization systems and mechanical venting of the fire floor. *ASHRAE Transactions* 96(2): 384-392.

Tamura, G.T. 1991. Determination of critical air velocities to prevent smoke backflow at a stair door opening on the fire floor. *ASHRAE Transactions* 97(2).

Tamura, G.T., and C.Y. Shaw. 1978. Experimental studies on mechanical venting for smoke control in tall office buildings. *ASHRAE Transactions* 84(2): 54-71.

Yoshida, H., C.Y. Shaw, and G.T. Tamura. 1979. A Fortran IV program to calculate smoke concentrations in a multi-storey building. National Research Council Canada. DBR Computer Program No. 45.