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Fire Tower Tests of Stair Pressurization Systems with Overpressure Relief

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Résumé

On a testé, dans une tour d'expérimentation incendie de 10 étages, des systèmes de pressurisation de cages d'escaliers selon divers schémas d'utilisation des portes d'escaliers, dans des conditions de non-incendie et d'incendie, et en été et en hiver. Les quatre systèmes en question comportaient les moyens suivants d'élimination de la surpression : élimination au moyen de la porte de sortie, élimination à l'aide de registres barométriques, commande par rétroaction utilisant une dérivation de ventilateur, et commande par rétroaction employant un ventilateur à vitesse variable. Les essais ont révélé que, dans les conditions mentionnées, l'utilisation de l'un ou l'autre des systèmes de pressurisation entraîne en principe l'envahissement de la cage d'escalier par la fumée si la porte d'escalier de l'étage du feu est ouverte et si celui-ci n'est pas ventilé sur l'extérieur. La cage d'escalier n'a pas été envahie par la fumée lorsque l'étage en feu a été ventilé au moyen d'ouvertures dans le mur extérieur, mais elle l'a été lorsqu'on a ouvert une ou plusieurs autres portes d'escaliers.

FIRE TOWER TESTS OF STAIR PRESSURIZATION SYSTEMS WITH OVERPRESSURE RELIEF

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ABSTRACT

Stairshaft pressurization systems were investigated under various schedules of stair door operation and nonfire/fire and summer/winter conditions in a 10-story experimental fire tower. The four stairshaft pressurization systems that were tested had overpressure relief features of exit door relief, barometric damper relief, feedback control with fan bypass, and feedback control with variable-speed fan. Tests have indicated that, under the conditions tested with any one of the stair pressurization systems on, smoke contamination of the stairshaft can be expected when the stair door on the fire floor is open and the fire floor is not vented to the outdoors. Smoke contamination of the stairshaft was prevented when the fire floor was vented by means of outside wall openings; however, the stairshaft was contaminated when one or more additional stair doors were opened.

INTRODUCTION

An ASHRAE research project was undertaken to evaluate the performance of stair pressurization systems with overpressure control. The first phase of the project involved reviewing the literature on stair pressurization systems, evacuation, and code requirements (Tamura 1989). It also involved conducting tests in a 10-story experimental fire tower to determine flow coefficients of open stair doors and the air velocities required to prevent smoke backflow at the open stair door on the fire floor. The second phase involved field evaluation of stairshaft pressurization systems with exit door relief in a 23-story apartment building, barometric damper relief in a 39-story office building, and feedback control with a variable-pitch blade fan in a 42-story office building (Tamura 1990).

The third phase of the project, which is the subject of this paper, involved evaluating the performance of the stair pressurization systems in a 10-story experimental fire tower with operation of stair doors under nonfire/fire and summer/winter conditions, with and without exterior wall venting of the fire floor. Tests were also conducted to evaluate the performance of the stair pressurization systems operating together with the mechanical exhaust system that was set to exhaust the second floor (fire floor); the results of these tests are given in a companion paper (Tamura 1990). The four stair pressurization systems that were investigated had overpressure relief features of exit door relief, barometric damper relief, feedback control with fan bypass, and feedback control with a variable-speed fan.

EXPERIMENTAL FIRE TOWER

All tests were conducted in a 10-story experimental fire tower located near Ottawa, Ontario. The details of the experimental fire tower were described in Tamura (1989). The floor plan showing the location of the test stairshaft is reproduced in Figure 1. The leakage areas of the tower were set to simulate those of a building with average airtightness and a floor area of 9730 ft^2 (904 m^2), or seven times that of the floor area of the experimental fire tower. The values of leakage areas for the tower given in Table 1 were arrived at from measurements of other buildings conducted by Tamura and Shaw (1976, 1978).

The experimental fire tower was equipped with various overpressure relief features, as shown in Figure 2. The

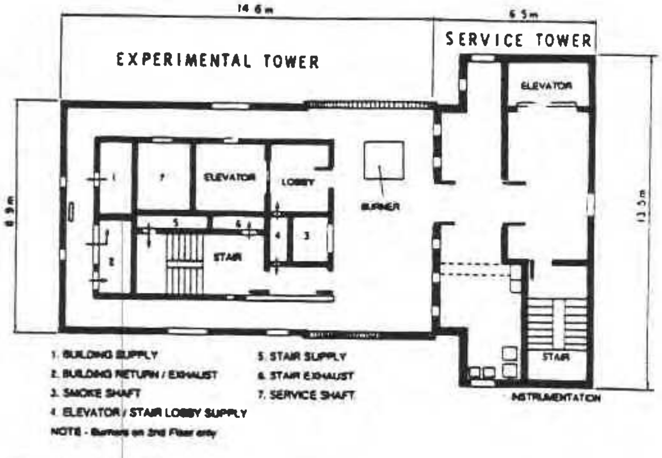

Figure 1 *Plan of the experimental fire tower*

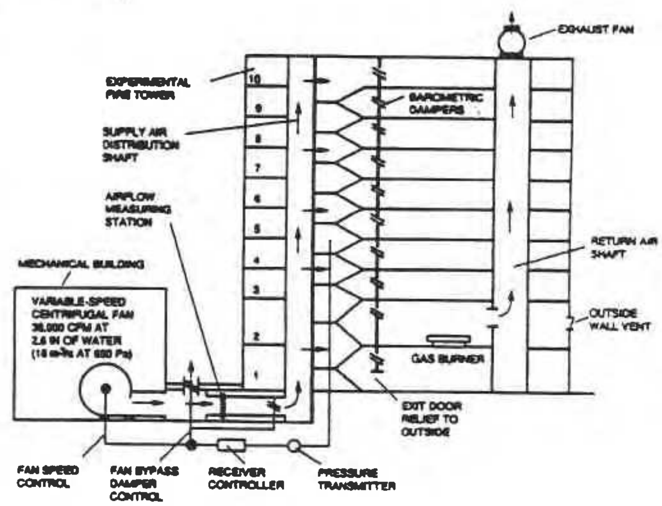

Figure 2 *Experimental fire tower with test equipment*

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supply air shaft is adjacent to the stairshaft with air outlet openings to permit injection of supply air on any floor. The supply air duct system is connected to a centrifugal fan in the adjacent mechanical building. The fan has a capacity of 38,000 cfm at 2.6 in. of water (18 m^3/s at 650 Pa) and a variable-speed drive. The airflow measuring station is located in the ductwork connected to the bottom of the air distribution shaft. It consists of multi-point self-averaging total pressure tubes and their associated static pressure taps (Ma 1967) and an air straightener of honeycomb panel located immediately upstream of the averaging tubes. Two propane gas burner sets, each capable of producing heat at an output of 8.5 million Btu/h (2.5 MW), are located on the second floor. Outside wall vents in the east and west walls of the second floor, each with an area of 5 ft^2 (0.464 m^2), can be opened remotely during a fire test to simulate broken windows.

For the stair pressurization system with exit door relief, the stair door and the exit door on the first floor can be opened to provide pressure relief to the outdoors. For the stairshaft pressurization system with barometric damper relief, a barometric damper 3 ft by 3 ft (0.91 m by 0.91 m) with three horizontal blades and an adjustable counterweight was installed in the stairshaft wall at each floor on the corridor side to provide pressure relief to the adjacent floor space.

For the stairshaft pressurization system with feedback control, a static pressure transmitter was located on the fifth floor of the service tower with the transmitter connected with plastic tubings to the pressure taps inside the stairshaft and the floor space of the same floor of the experimental fire tower. The receiver controller was located in the control room of the single-story service building adjacent to the tower. By means of a four-position switch, the controller can be set to control either the two motorized dampers of the fan bypass or the variable-speed drive of the centrifugal fan to maintain the pressure difference across the stair door on the fifth floor at the setpoint by varying the supply air rate to the stairshaft.

TABLE 1
Leakage Flow Areas per Floor of the Experimental Fire Tower

Location	Area ft^2	Area m^3
Outside walls		
1st floor east wall	0.59	0.055
1st floor floor west wall	0.59	0.055
2nd floor east wall (wall vent closed)	0.59	0.055
2nd floor east wall (wall vent open)	5.00	0.464
2nd floor west wall (wall vent closed)	0.59	0.055
2nd floor west wall (wall vent closed)	5.00	0.464
Typical floor east wall	0.39	0.037
Typical floor west wall	0.39	0.037
Elevator		
Floor space to elevator shaft	0.07	0.006
Floor space to elevator lobby (lobby door closed)	0.30	0.028
Floor space to elevator lobby (lobby door open)	21.00	1.951
Elevator lobby to elevator shaft (elevator doors closed)	0.75	0.070
Elevator lobby to elevator shaft (elevator doors open)	6.00	0.557
Stairs		
Floor space to stairshaft	0.04	0.004
Floor space to stair lobby (lobby door closed)	0.25	0.023
Floor space to stair lobby (lobby door open)	21.00	1.951
Stair lobby to stairshaft (stair door closed)	0.25	0.023
Stair lobby to stairshaft (stair door open)	21.00	1.951
Vertical Shafts		
Floor space to service shaft	1.10	0.102
Floor space to supply air shaft*	2.00	0.186
Floor space to return air shaft*	2.00	0.186
Ceiling	0.56	0.052

*Supply and return air openings sealed on the 2nd floor

TEST PROCEDURE

For all tests, the door-opening sequence was essentially the same as the one used during the Phase 2 field tests, with the second floor designated as the fire floor and stair doors on the exit floor, fire floor, one above the fire floor, and one of the upper floors opened sequentially. For all pressurization systems, the supply air was injected inside the stairshaft on floors 1, 3, 5, 7, and 10. The stairshaft pressurization systems were tested under the following schedules:

Nonfire Tests with Stairshaft Pressurization:

1. No doors open
2. Stair doors open on Floors 1 and 2
3. Stair doors open on Floors 1, 2, and 3
4. Stair doors open on Floors 1, 2, 3, and 8

Measurements were conducted with the above door-opening schedule, first with the exterior wall vents on the second floor closed and then with them open.

Fire Tests with Stairshaft Pressurization:

1. At a fire temperature of 840°F (450°C) and with the exterior wall vents on the second floor closed (intended as a low-temperature fire), the above door-opening sequence was followed until a backflow at the stair door opening on the second floor was observed. The stair door opening on the fire floor was decreased until backflow was prevented and the door angle at the point of no backflow was noted. Exterior wall vents on the second floor were opened for some of the low-temperature fire tests to determine their effect on air velocities at the stair door opening on the same floor.

2. At fire temperature of 1200°F (650°C) and with the exterior wall vents open (intended as a high-temperature fire), the above door-opening sequence was followed until a backflow at the stair door opening on the second floor was observed. The stair door was again gradually closed and the door angle at the point of no backflow was noted.

Pressure differences across stair doors were measured with a diaphragm-type magnetic reluctance pressure transducer and the supply air rates for stairshaft pressurization were measured at the flow-measuring station. Temperatures were measured with chromel-alumel thermocouples. The average air velocities at the stair door opening on the second floor during nonfire tests were measured by carrying out a 21-point hot-wire anemometer traverse. They were averaged to obtain the average air velocity. Smoke backflow during the fire tests was determined with smoke sticks at the stair door opening on the second floor. Carbon dioxide concentrations in the tower were measured with nondispersive infrared gas analyzers.

The stair pressurization systems were tested under both summer and winter conditions. Pressure measurements were conducted in winter without stairshaft pressurization to determine the influence of stack action on pressure

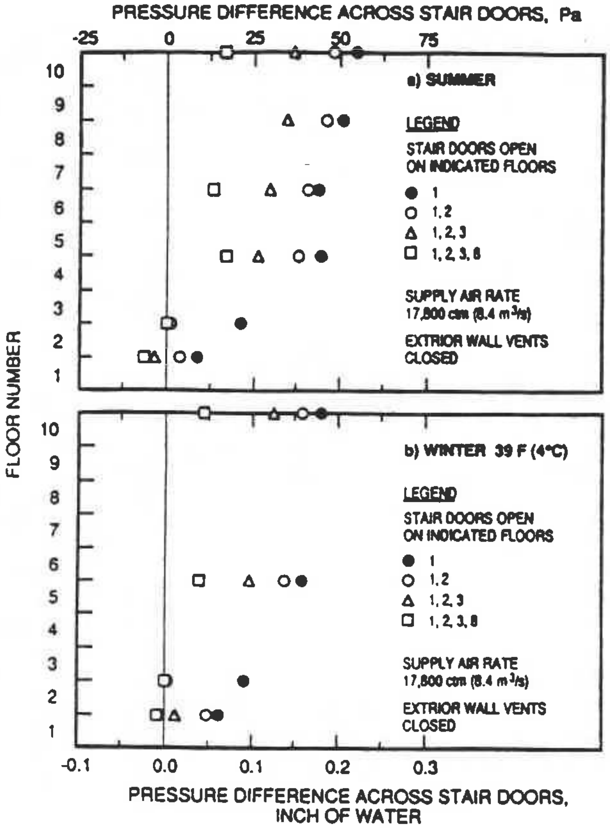

Figure 3 Pressure difference measurements of stair pressurization system with exit door relief, nonfire conditions

differences across the stair doors and on airflow velocities at the stair door opening on the second floor. They were conducted with either the exterior wall vents on the second floor or the stair door on the first floor open and also with a combination of both.

Tests were conducted to check the feedback control system of the stairshaft pressurization systems with fan bypass and the variable-speed drive fan. The response time of both pressurization systems to changes in stairshaft pressures caused by opening and closing of stair doors were obtained by recording, on chart recorders, the pressure differences across the second floor stair door and the rate of supply air for pressurization.

For the feedback control systems, tests were also conducted to find a suitable location for the reference pressure side of the static pressure transmitter to prevent overpressurization of the stairshaft. With the reference pressure tap located on the fifth floor, either in the floor space or inside the service shaft, pressure differences across the stair door on the second floor were measured with the stair door on the fifth floor closed and then open. Also, to check the suitability of the rooftop as the reference pressure, pressure differences between the stairshaft and the adjacent floor space and that between the stairshaft and rooftop were read on the chart recorder under various wind conditions.

RESULTS AND DISCUSSION

Stair Pressurization System with Exit Door Relief

Nonfire Conditions Pressure differences across the stair doors for summer in the nonfire condition are shown in Figure 3a. The supply air rate for pressurization was 17,800 cfm (8.40 m^3/s) to produce a pressure difference across the stair door on the second floor of 0.10 in. of water (25 Pa) with all stair doors closed except for the one on the first floor leading to the outdoors. The pressure differences were the smallest, 0.036 in. of water (10 Pa), on the first floor across the stair door leading to the floor space, and they were largest (0.218 in. of water [54 Pa]) on the tenth floor. This pressure pattern was caused by the flow resistance of the stairway with pressure drops occurring downward in the direction of flow toward the open exit door. The pressure differences decreased as the stair doors on floors 2, 3, and 8 were opened in succession. Except for floors 1 and 2, all the pressure differences were above 0.10 in. of water (25 Pa) when the doors on floors 1, 2, and 3 were opened, and they were above 0.05 in. of water (12.5 Pa) when the door on floor 8 was also opened. The pressure differences on floor 2 were near zero, and those on floor 1 were above and below zero in all cases. Pressure differences measured during winter with an outside temperature of 39°F (4°C) are shown in Figure 3b. The pressure pattern in winter is similar to that of summer. Compared with the summer readings, the pressure differences were lower above the second floor, but they were higher on the first and second floors.

Table 2a gives the pressure difference and the average air velocities at the open stair door on the second floor measured during the door-opening tests with the exterior wall vents on the second floor closed and open. The measurements were conducted with no fire under both summer and winter conditions. Without exception, both the average air velocities and pressure differences were greater with the exterior wall vents open than with them closed, and they were greater for winter than for summer conditions. With the exterior wall vents closed, the pressure differences were near zero, whereas with them open, the pressure differences varied from 0.008 to 0.016 in. of water (2 to 4 Pa). For the summer conditions, the average air velocities varied from 33 to 118 fpm (0.17 to 0.60 m/s) with the exterior wall vents closed as compared to 197 to 285 fpm (1.00 to 1.45 m/s) with them open. For the winter conditions, the average air velocities varied from 59 to 143 fpm (0.30 to 0.73 m/s) with the exterior wall vents closed as compared to 236 to 320 fpm (1.2 to 1.63 m/s) with them open.

Fire Conditions Table 2b gives the observations of smoke backflow into the stairshaft at the open stair door on the second floor during the fire tests. For both the winter and summer conditions with a fire temperature of 850°F (454°C), smoke backflow occurred when the stair doors on the first and second floors were open and the exterior wall vents were closed. Smoke backflow, however, was prevented when the exterior wall vents were open. The average air velocity for the nonfire conditions corresponding to the latter case was 285 fpm (1.45 m/s). When the stair door on the third floor was also opened, smoke backflow occurred for the summer and winter conditions with a greater amount of backflow for the summer conditions. With a fire temperature of 1200°F (650°C), the first and second floor stair doors open, and the exterior wall vents open, smoke backflow occurred for the summer conditions but not for the winter conditions. For the latter conditions, the average air velocity was 320 fpm (1.63 m/s) for the corresponding nonfire conditions. Under the winter conditions when the stair door on the third floor was also opened, smoke backflow occurred.

Smoke backflow can be prevented by partially closing the door on the second floor. The required door angles to accomplish this are also given in Table 2b for the various test conditions. For example, when stair doors on the first and second floors are open and the exterior wall vents closed, smoke backflow can be prevented with a door angle on the second floor of 10° in summer and 17° in winter.

Pressure differences measured under nonfire conditions indicated that the average air velocities at the second floor stair door were considerably higher when the exterior wall vents were open than when they were closed. The total area of the vent openings was 10 ft^2 (0.93 m^2). With a stair door opening of 20 ft^2 (1.86 m^2), from series flow considerations, a larger vent size would have resulted in greater air velocities. It would, therefore, be expected that mechanical venting of the fire floor would also result in air velocities greater than those with exterior wall vents closed.

Because of stack action with the exit door open to the outdoors, the stair pressurization system performed better under winter than under summer conditions.

Stair Pressurization System with Barometric Damper Relief

With all stair doors closed, the counterweights of the barometric dampers were set to give a pressure difference across the stair doors of 0.40 in. of water (100 Pa), which is the maximum allowable pressure difference across the stair door to avoid door-opening problems. The blade angles of the barometric dampers were about 35° open and the corresponding supply air rate was 28,000 cfm (13.2 m^3/s), a much greater rate than for the stairshaft pressurization system with exit door relief of 17,800 cfm (8.40 m^3/s).

Nonfire Conditions Pressure differences across the stair doors for summer in nonfire conditions are shown in Figure 4a. With all stair doors closed, the pressure differences were just above 0.40 in. of water (100 Pa). With all doors closed except for the one on the first floor leading to the outdoors, the pressure difference was least on the first floor across the stair door leading to the floor space,

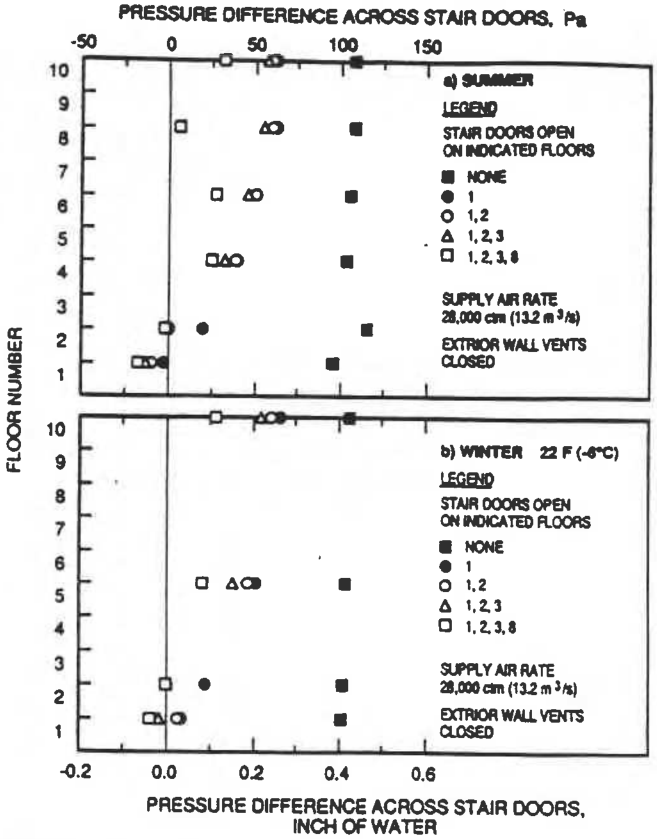

Figure 4 *Pressure difference measurements of stair pressurization system with barometric damper relief, nonfire conditions*

TABLE 2
Pressure Difference, Average Air Velocity, and Smoke Backflow Measurements at Stair Door Opening on the Fire Floor (Second Floor) of Stairshaft Pressurization System with Exit Door Relief

2a Nonfire Condition

Open Doors, Floor	Supply Air Rate scfm (m^3/s)	Outside Wall Vents	Pressure Difference in. of Water (Pa)	Average Air Velocity fpm (m/s)
Summer Condition—68°F (20°C), 6 mph (10 kmh) southeast				
1,2	17,800 (8.40)	closed	0.005 (1.2)	118 (0.60)
"	"	open	0.016 (4.0)	285 (1.45)
1,2,3	"	closed	0.000 (0.0)	57 (0.29)
"	"	open	0.010 (2.5)	244 (1.24)
1,2,3,8	"	closed	0.000 (0.0)	33 (0.17)
"	"	open	0.008 (2.0)	197 (1.00)
Winter Condition—39°F (4°C), 13 mph (21 kmh) west				
1,2	17,800 (8.40)	closed	0.005 (1.2)	143 (0.73)
"	"	open	0.016 (4.0)	320 (1.63)
1,2,3	"	closed	0.000 (0.0)	83 (0.42)
"	"	open	0.010 (2.5)	268 (1.36)
1,2,3,8	"	closed	0.000 (0.0)	59 (0.30)
"	"	open	0.010 (2.5)	236 (1.20)

2b Fire Condition

Open Doors, Floor	Supply Air Rate scfm (m^3/s)	Outside Wall Vents	Fire Temp. °F (°C)	Smoke Backflow, % of Door Area	Door Angle to Stop Smoke Backflow Degree
Summer Condition—68°F (20°C), 6 mph (10 kmh) southeast					
1,2	17,800 (8.40)	closed	824 (440)	35	10
"	"	open	840 (485)	0	-
1,2,3	"	"	942 (506)	25	26
1,2	"	"	1175 (635)	20	43
1,2,3	"	"	"	30	23
Winter Condition—39°F, (4°C), 13 mph (21 kmh) west					
1,2	17,800 (8.40)	closed	850 (454)	35	17
"	"	open	"	0	-
1,2,3	"	"	"	1	90
1,2,3,8	"	"	"	10	37
1,2	"	"	1200 (650)	0	-
1,2,3	"	"	"	10	67

with a value of -0.012 in. of water (-3 Pa), and was highest on the tenth floor at 0.25 in. of water (62 Pa). This pressure pattern is similar to that of the stairshaft pressurization system with exit door relief. The pressure differences decreased as the stair doors on floors 2, 3, and 8 were opened in succession. Except for floors 1 and 2, the pressure differences across all closed doors were above 0.10 in. of water (25 Pa) when doors on floors 1, 2, 3, and 8 were opened. The pressure difference on floor 2 was 0.08 in. of water (20 Pa) when only the stair door on floor 1 was open, and it was near zero when additional doors were opened. Pressure differences on floor 1 were negative except for the case with all doors closed. Pressure differences measured during winter with an outdoor temperature of 22°F (-6°C) are shown in Figure 4b. The pressure pattern in winter is much the same as in summer, except that the pressure differences on the first and second floors are somewhat higher in winter than in summer. This was also the case with the stair pressurization system with exit door relief. The influence of stack action on these pressure differences is discussed later.

Damper positions during the door-opening tests are given in Table 3. On floors where the stair doors were opened, the dampers closed completely with no further influence on the stairshaft pressures; on other floors, they remained in their initial position or were closed by a varying amount.

Table 4a gives the pressure differences and the average air velocities at the open stair door on the second floor during the door-opening test with the exterior wall vents on the second floor closed and open. The measurements were conducted with no fire under both summer and winter conditions. Both the average air velocities and pressure differences were greater with the exterior wall vents open than with them closed, and they were greater for the winter than for the summer conditions. With the exterior wall vents closed, the pressure differences were near zero, whereas with them open, the pressure differences were about 0.011 in. of water (3 Pa) in summer and 0.013 to 0.018 in. of water (3 to 4 Pa) in winter. For summer conditions, the average air velocities varied from 43 to 106 fpm (0.22 to 0.54 m/s) with the exterior wall vents closed, as compared to 246 to 309 fpm (1.25 to 1.57 m/s) with them open. For winter conditions, the average air velocities varied from 48 to 158 fpm (0.25 to 0.81 m/s) with the exterior wall vents closed, as compared to 280 to 380 fpm (1.43 to 1.93 m/s) with them open.

Fire Conditions Table 4b gives the results of the fire tests. For both the winter and summer conditions with a fire

TABLE 3
Damper Positions of Stairshaft Pressurization Systems with Barometric Damper Relief

	Damper Position, % Opening				
	Stair Doors Open on Indicated Floors				
Floor	None	1	1,2	1,2,3	1,2,3,8
10	35	35	35	35	35
9	35	35	35	35	33
8	30	26	25	25	0
7	33	28	28	26	18
6	23	20	16	16	8
5	38	39	38	35	26
4	33	30	23	20	0
3	35	16	16	0	0
2	43	0	0	0	0
1	38	0	0	0	0

TABLE 4
Pressure Difference, Average Air Velocity, and Smoke Backflow Measurements at Stair Door Opening on the Fire Floor (Second Floor) of Stairshaft Pressurization System with Barometric Damper Relief

Open Doors, Floor	Supply Air Rate scfm (m³/s)	Outside Wall Vents	Pressure Difference in. of Water (Pa)	Average Air Velocity fpm (m/s)
4a Nonfire Conditon				
Summer Condition—82°F (28°C), 6 mph (10 kmh) northwest				
1,2	28,000 (13.2)	closed	0.000 (0.0)	106 (0.54)
"	"	open	0.011 (2.7)	309 (1.57)
1,2,3	"	closed	−0.004 (−1.0)	53 (0.27)
"	"	open	0.011 (2.7)	270 (1.37)
1,2,3,8	"	closed	−0.007 (−1.7)	43 (0.22)
"	"	open	0.011 (0.0)	246 (1.25)
Winter Condition— −22°F (−6°C), 9 mph (15 kmh) southwest				
1,2	28,000 (13.2)	closed	0.001 (0.2)	158 (0.81)
"	"	open	0.018 (4.5)	380 (1.93)
1,2,3	"	closed	0.001 (0.2)	97 (0.49)
"	"	open	0.018 (4.5)	345 (1.74)
1,2,3,8	"	closed	−0.003 (−0.7)	48 (0.25)
"	"	open	0.013 (3.2)	281 (1.43)

Open Doors, Floor	Supply Air Rate scfm (m³/s)	Outside Wall Vents	Fire Temp. °F (°C)	Smoke Backflow, % of Door Area	Door Angle to Stop Smoke Backflow Degree
4b Fire Condition					
Summer Condition—68°F (20°C), 6 mph (10 kmh) southeast					
1,2	28,000 (13.2)	closed	932 (500)	35	10
1,2	"	open	833 (445)	0	-
1,2,3	"	"	852 (456)	0	-
1,2,3,8	"	"	"	10	73
1,2,3	"	"	1178 (637)	15	37
Winter Condition— −22°F, (−6°C), 9 mph (15 kmh) southwest					
1,2	28,000 (8.40)	closed	840 (450)	40	13
1,2,3	"	open	"	0	-
1,2,3,8	"	"	"	0	-
1,2,3	"	"	1200 (650)	0	-
1,2,3,8	"	"	"	10	-

temperature of 850°F (454°C), smoke backflow occurred when the stair doors were open on the first and second floors and the exterior wall vents closed, whereas smoke backflow was prevented with the exterior wall vents open. Under summer conditions with the exterior wall vents open, smoke backflow was also prevented when the stair door on the third floor was opened. The average air velocity was 270 fpm (1.37 m/s) for the corresponding nonfire conditions. Smoke backflow occurred, however, when the stair door on the eighth floor was opened too. Also under summer conditions, at a fire temperature of 1200°F (650°C) smoke backflow occurred when the doors on floors 1, 2, and 3 were open. Under the winter condition with the exterior wall vents open, smoke backflow was prevented when doors on floors 1, 2, 3, and 8 were open at fire temperatures of 840°F (450°C) and 1200°F (650°C). For the latter fire temperature, the average air velocity was 281 fpm (1.43 m/s) for the corresponding nonfire conditions.

The stair pressurization system with barometric damper relief performed better than the system with exit door relief in terms of the number of doors open without smoke backflow at the stair door opening on the second floor. However, the supply air rate for pressurization of the stair pressurization system with barometric damper relief was about one-and-a-half times that of the stair pressurization system with exit door relief.

Stair Pressurization System with Fan Bypass

The setpoint of the receiver controller of the feedback control was set nominally at 0.10 in. of water (25 Pa) across the stair door on the fifth floor. The pressure transmitter was located on the fifth floor, connected by plastic tubings on the one side to the stairshaft and on the other side to the floor space of the same floor.

Nonfire Conditions Pressure differences across the stair doors for the summer and nonfire conditions are shown in Figure 5a. With all doors closed, the pressure differences were just above 0.10 in. of water (25 Pa). The supply air rate for pressurization was 1700 cfm (0.81 m^3/s). The pressure differences above the third floor remained at this pressure difference when the stair doors on floors 1, 2, 3, and 8 were opened in succession. The supply air rates increased to 13,300; 14,300; 17,200; and 30,000 cfm (6.26, 6.75, 8.13, 14.14 m^3/s), respectively, with the above sequence of stair door opening. When the stair doors were open on floors 1, 2, and 3, the supply air rates were about equal to that of the pressurization system with exit door relief. When the stair door on the eighth floor was opened as well, the supply air rate was more than that of the pressurization system with barometric damper relief. Pressure differences on floors 1 and 2, however, fell well below the setpoint value when the stair doors were opened, as shown in Figure 5a.

A separate test was conducted with all stair doors closed except for the one on the fifth floor, where the pressure transmitter for the controller is located. Although the pressure difference across the stair door on the fifth floor was controlled at 0.10 in. of water (25 Pa), those on other floors increased to about 0.60 in. of water (149 Pa), which can make door opening difficult.

Pressure differences measured during winter with an outdoor temperature of 21°F (-6°C) are shown in Figure 5b. The pressure pattern in winter is similar to that of summer, except that the pressure differences of the first and second floors are higher than those in summer, as for the two previous pressurization systems.

Table 5a gives the pressure differences and the average air velocities at the open stair door on the second floor during the door-opening test with the exterior wall vents on

TABLE 5
Pressure Difference, Average Air Velocity, and Smoke Backflow Measurements at Stair Door Opening on the Fire Floor (Second Floor) of Stairshaft Pressurization System with Fan Bypass

5a Nonfire Conditon

Open Doors, Floor	Supply Air Rate scfm (m^3/s)	Outside Wall Vents	Pressure Difference in. of Water (Pa)	Average Air Velocity fpm (m/s)
Summer Condition—68°F (20°C), 6 mph (10 kmh) southeast				
1,2	14,300 (6.75)	closed	0.005 (1.2)	130 (0.66)
"	15,250 (7.20)	open	0.012 (3.0)	290 (1.48)
1,2,3	17,200 (8.13)	closed	0.002 (0.5)	87 (0.44)
"	17,700 (8.37)	open	0.011 (2.7)	254 (1.29)
1,2,3,8	30,000 (14.14)	closed	0.000 (0.0)	55 (0.28)
"	31,100 (14.69)	open	0.012 (3.0)	275 (1.40)
Winter Condition— - 21°F (- 6°C), 12 mph (20 kmh) southwest				
1,2	13,100 (6.18)	closed	0.005 (1.2)	142 (0.73)
"	15,400 (7.28)	open	0.020 (5.0)	327 (1.66)
1,2,3	16,950 (8.00)	closed	0.003 (0.7)	94 (0.48)
"	19,150 (9.03)	open	0.018 (4.5)	306 (1.55)
1,2,3,8	31,200 (14.73)	closed	0.001 (0.2)	74 (0.38)
"	33,000 (15.60)	open	0.019 (4.7)	339 (1.70)

5b Fire Condition

Open Doors, Floor	Supply Air Rate scfm (m^3/s)	Outside Wall Vents	Fire Temp. °F (°C)	Smoke Backflow, % of Door Area	Door Angle to Stop Smoke Backflow Degree
Summer Condition—63°F (17°C), 5 mph (8 kmh) northwest					
1,2	13,250 (6.26)	closed	840 (450)	40	10
1,2	15,250 (7.2)	open	880 (470)	5	56
1,2,3	18,000 (8.5)	"	914 (490)	-	45
1,2	14.950 (7.05)	"	1200 (650)	15	28
1,2,3	17,500 (8.25)	"	1230 (670)	25	32
Winter Condition— - 21°F, (- 6°C), 12 mph (20 kmh) southwest					
1,2	13,100 (6.18)	closed	840 (450)	40	14
1,2	16,100	open	"	0	-
1,2,3	18,600	"	"	0	-
1,2,3,8	30,800	"	"	0	-
1,2,3,8	32,200 (15.18)	"	1200 (650)	0	-

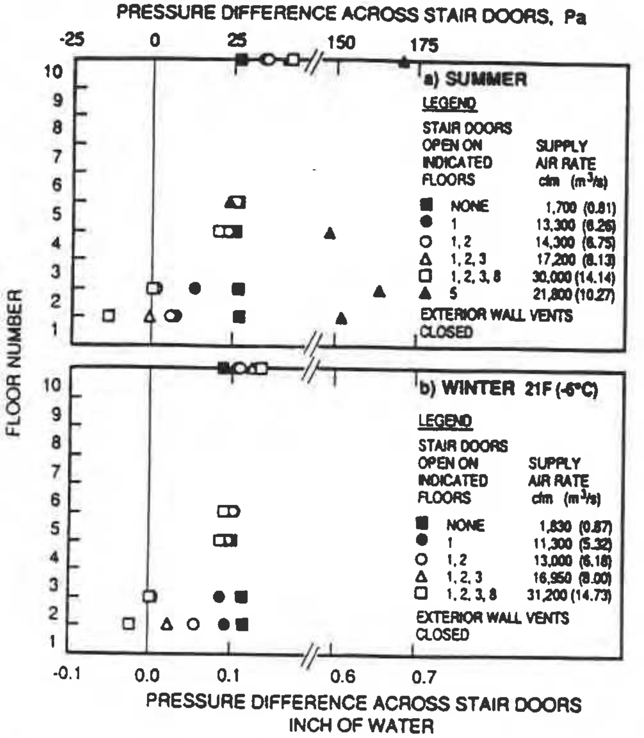

Figure 5 *Pressure difference measurements of stair pressurization system with fan bypass (reference pressure for the controller on the 5th floor), nonfire conditions*

the second floor closed and open. The measurements were conducted with no fire under both summer and winter conditions. Both the average air velocities and pressure differences were greater with the exterior wall vents open than with them closed, and they were greater for winter than for summer. With the exterior wall vents closed, the pressure differences were near zero for both summer and winter, whereas with them open, the pressure differences were about 0.012 in. of water (3 Pa) in summer and about 0.019 in. of water (5 Pa) in winter. For summer conditions, the average air velocities varied from 55 to 130 fpm (0.28 to 0.66 m/s) with the exterior wall vents closed as compared to 275 to 290 fpm (1.40 to 1.48 m/s) with them open. For winter conditions, the average air velocities varied from 74 to 142 fpm (0.38 to 0.73 m/s) with the exterior wall vents closed as compared to 327 to 339 fpm (1.66 to 1.70 m/s) with them open.

Fire Tests Table 5b gives the results of the fire tests. For summer conditions with a fire temperature of 850°F (454°C), smoke backflow occurred when the stair doors were open on the first and second floors and the exterior wall vents were closed; smoke backflow also occurred with them open but was considerably less than with them closed. For winter conditions, smoke backflow also occurred when the stair doors on the first and second floors were open and with the exterior wall vents closed. With the exterior wall vents open, however, there was no smoke backflow with stair doors open on floors 1, 2, 3, and 8 at fire temperatures of 840°F (450°C) and 1200°F (65°C). For the corresponding nonfire case, the average air velocity was 339 fpm (1.70 m/s). The minimum average air velocity for the conditions tested was 306 fpm (1.55 m/s) with stair doors open on floors 1, 2, and 3 at a fire temperature of 840°F (450°C).

With this system under conditions of summer and a low-temperature fire, smoke backflow occurred with the stair doors open on the first and second floors and the exterior wall vents open, whereas it did not occur with the stair pressurization system with exit door relief or with barometric damper relief. This was probably due to the supply air rate of the fan bypass system being lower than those of the two other systems for this test condition.

Examination of Feedback Control System With the reference pressure tap of the static pressure transmitter located on the floor space of the fifth floor, the stairshaft was highly overpressurized when the door on that floor was opened (Figure 5a). To avoid this, the reference pressure tap of the static pressure transmitter was moved from the floor space to inside the service shaft on the same floor. With the stairshaft pressurized, the stair door was opened on the fifth floor; the pressure difference across the stair door on the second floor was 0.114 in. of water (28 Pa). It was considerably less than the pressure difference across the stair door on the second floor of 0.640 in. of water (160 Pa) (see Figure 5a) obtained with the reference pressure in the floor space of the fifth floor and with the stair door on this floor open.

To investigate the suitability of the rooftop as a reference pressure, pressure differences between the stairshaft and floor space and that between the stairshaft and rooftop in a sheltered area were recorded on a chart recorder for wind speeds of 2.5 mph (4 kmh), 13 mph (21 kmh), and 18 mph (30 kmh); the stairshaft was not pressurized. The pressure differences between the stairshaft and floor space remained steady at zero readings for the two lower wind speeds; that for the highest wind speed was -0.01 ±0.002 in. of water (-2.5 ±0.5 Pa). The pressure differences between the stairshaft and rooftop, however, were -0.017 in. of water (-4 Pa) with small fluctuations for a wind speed of 2.5 kmh (4 kmh), -0.040 ±0.060 in. of water (-10 ±15 Pa) for a wind speed of 13 mph (21 kmh), and -0.06 ±0.10 in. of water (15 ±25 Pa) for a wind speed of 18 mph (30 kmh). These readings indicate that with the reference pressure tap at the rooftop, the static pressure controller can be affected by wind pressures. These tests indicated that the most suitable location for the reference pressure tap was inside the service shaft.

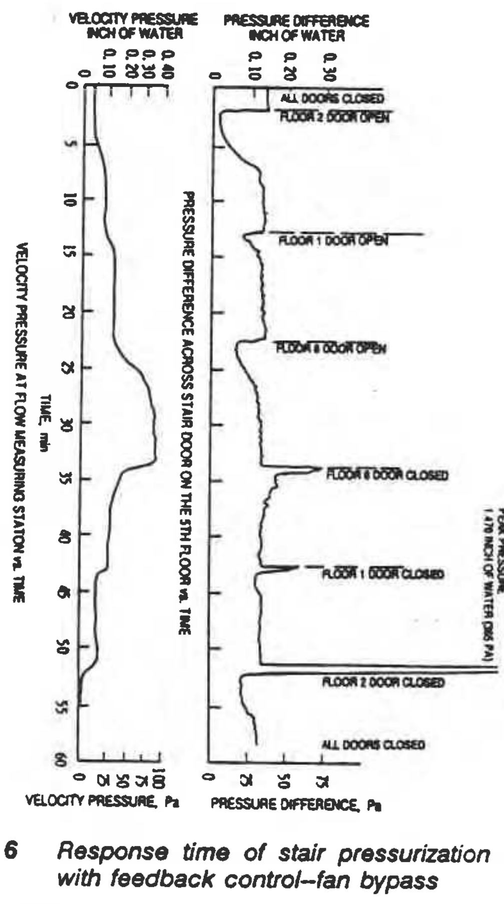

Figure 6 *Response time of stair pressurization system with feedback control--fan bypass*

The performance of the feedback controller is illustrated in Figure 6. The pressure difference across the stair door on the fifth floor and the velocity pressure of the airflow-measuring station with respect to time are shown when the stair doors were opened sequentially. Initially, the pressure difference was 0.133 in. of water (33 Pa). When the stair door on the second floor was opened, the pressure difference decreased sharply and then increased gradually to return to its initial reading. It took 10.5 minutes to reach its initial reading and 5 minutes to reach 75% of its original reading; when the stair doors on the first and then the eighth floor were opened, the response times were 6 minutes and 1.2 minutes, and 8.5 minutes and 4 minutes, respectively. When the stair doors were closed in the reverse order, the pressure difference increased momentarily and then decreased to its original reading. The times to reach this reading were 5 minutes, 4.5 minutes, and 5.5 minutes when the stair doors on the eighth, first, and second floors were closed in turn. When the last door was closed, the pressure difference increased to a peak of 1.470 in. of water (365 Pa) with a loud laboring sound from the fan and dropped to 0.30 in. of water (75 Pa) in 50 s. Because of the lag of the feedback control system, smoke contamination of the stairshaft can occur momentarily due to a loss of pressurization when stair doors are opened.

Stair Pressurization System with Variable-Speed Fan

The results of the measurements for this system, which are given in Figures 7a and 7b and Tables 6a and 6b, were similar to those of the stair pressurization system with fan bypass. The exception was that smoke backflow occurred for the high-temperature case under winter conditions when

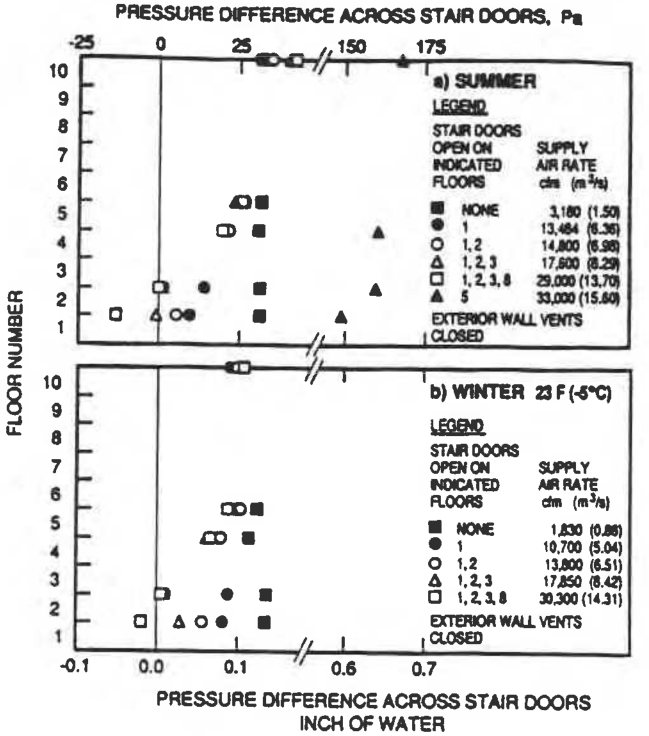

Figure 7 *Pressure difference measurements of stair pressurization system with variable-speed fan (reference pressure for the controller on the 5th floor), nonfire conditions*

TABLE 6
Pressure Difference, Average Air Velocity, and Smoke Backflow Measurements at Stair Door Opening on the Fire Floor (Second Floor) of Stairshaft Pressurization System with Variable-Speed Fan

6a Nonfire Conditon

Open Doors, Floor	Supply Air Rate scfm (m^3/s)	Outside Wall Vents	Pressure Difference in. of Water (Pa)	Average Air Velocity fpm (m/s)
Summer Condition—65°F (18°C), 2 mph (4 kmh)				
1,2	14,800 (7.00)	closed	0.004 (1.0)	117 (0.59)
"	16,000 (7.54)	open	0.015 (3.7)	260 (1.31)
1,2,3	17,560 (8.29)	closed	0.004 (1.0)	73 (0.37)
"	18,500 (8.74)	open	0.010 (2.5)	238 (1.20)
1,2,3,8	29,000 (13.7)	closed	0.000 (0.0)	45 (0.23)
"	30,150 (14.2)	open	0.016 (4.0)	258 (1.31)
Winter Condition— −23°F (−5°C), 12 mph (20 kmh) southwest				
1,2	13,800 (6.51)	closed	0.006 (1.50)	136 (0.69)
"	13,400 (6.32)	open	0.023 (5.7)	374 (1.90)
1,2,3	17,850 (8.42)	closed	0.005 (1.2)	102 (0.52)
"	18,700 (8.82)	open	0.018 (4.5)	367 (1.86)
1,2,3,8	30,300 (14.31)	closed	0.002 (6.5)	80 (1.89)
"	31,700 (14.35)	open	0.018 (6.5)	372 (1.89)

6b Fire Condition

Open Doors, Floor	Supply Air Rate scfm (m^3/s)	Outside Wall Vents	Fire Temp. °F (°C)	Smoke Backflow, % of Door Area	Door Angle to Stop Smoke Backflow Degree
Summer Condition—65°F (18°C), 2 mph (4 kmh)					
1,2	14,800 (7.00)	closed	860 (460)	40	10
1,2	16,400 (7.73)	open	"	0	-
1,2,3	19,000 (8.96)	"	932 (500)	15	36
1,2	16,000 (7.54)	"	1200 (650)	15	30
Winter Condition— −23°F, (−5°C), 12 mph (20 kmh) southwest					
1,2	12,540 (5.92)	closed	850 (454)	40	13
"	16,000 (7.54)	open	788 (420)	0	-
1,2,3	23,300 (7.54)	"	850 (454)	0	-
1,2,3,8	31,700 (15.0)	"	"	0	-
1,2,3	19,200 (9.08)	"	1200 (650)	20	38

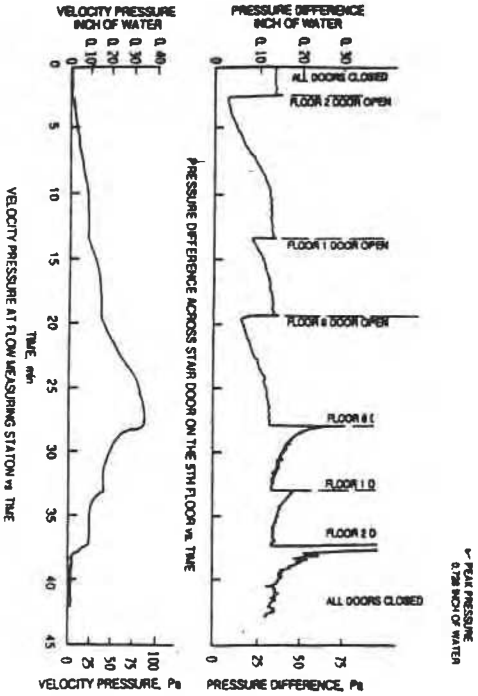

Figure 8 *Response time of stair pressurization system with feedback control–variable-speed fan*

stair doors on floors 1, 2, and 3 were open, whereas for the fan bypass system, smoke backflow was prevented when stair doors were open on floors 1, 2, 3, and 8.

Examination of Feedback Control System The performance of the pressure control system tested under the same condition as the bypass system is illustrated in Figure 8. When the stair doors on floors 2, 1, and 8 were opened in succession, it took 9 minutes, 5 minutes, and 7.6 minutes to reach its initial reading and 5 minutes, 1 minute, and 3.2 minutes to reach 0.10 in. of water (25 Pa) or 75% of its original reading. When the stair doors were closed in the reverse order, the pressure difference increased momentarily and then decreased to its original reading. It took 5 minutes, 2.7 minutes, and 5 minutes to reach these readings when the stair doors on the eighth, first, and second floors were closed in turn. When the last door was closed, the pressure difference peaked at 0.728 in. of water (180 Pa) and dropped to 0.30 in. of water (75 Pa) in 50 seconds. These response times are slightly less than those for the pressure control system of the stair pressurization system with fan bypass.

Pressure Differences across Stair Doors Caused by Stack Action

Comparison of the pressure differences across the stair doors measured during winter and summer tests indicated that when the stair door on the first floor was opened to the outdoors, the pressure differences at the lower floors were more favorable in winter than in summer. Consequently, in winter during the door-opening tests, the average air velocities at the door opening on the second floor were higher and the stair pressurization system performed better in preventing smoke backflow than in summer.

The results of pressure measurements conducted at an outdoor temperature of 30°F (-1°C) and without stairshaft pressurization are shown in Figure 9. The wind speed was 12 mph (19 kmh), which may have distorted somewhat the pressure differences caused by stack action. With all stair doors closed, the neutral pressure level of the stairshaft is located at about the mid-height of the tower. The pressure

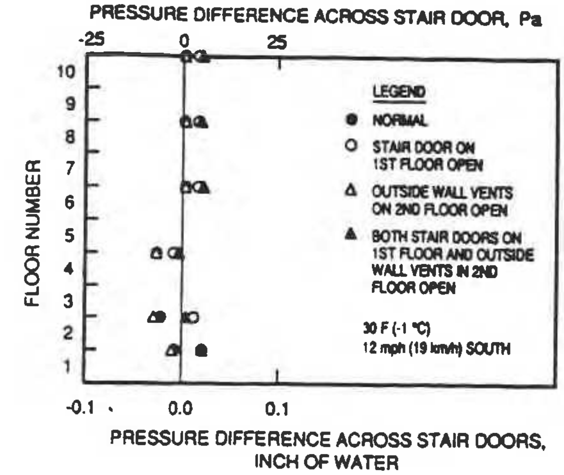

Figure 9 *Pressure differences across stair doors caused by stack action*

differences across the stair doors on the first and second floors are -0.008 in. of water (-2 Pa) and -0.023 in. of water (-6 Pa), respectively, with air flowing from the floor spaces to the stairshaft. When the stair door on the first floor leading to the outdoors was opened, the direction of airflow reversed, with pressure differences of 0.022 in. of water (5 Pa) for the first floor and 0.013 in. of water (3 Pa) for the second floor. When the stair door on the first floor was closed and the outside wall vents on the second floor were opened, the pressure differences across the first and second floor doors were -0.010 in. of water (-3 Pa) and -0.030 in. of water (-7 Pa), respectively. When both the stair door on the first floor and the outside wall vents on the second floor were opened, the pressure differences across the first and second floors were 0.022 in. of water (5 Pa) and 0.005 in. of water (1 Pa).

These measurements indicate that stack action under winter conditions can assist stair pressurization systems when the stair door on the first floor is opened to the outdoors. On the other hand, opening the exterior wall vents on one of the lower floors, simulating broken windows, can have a negative effect. However, when the stairshaft is pressurized, the average air velocities at the stair door opening with the exterior wall vents open are considerably greater than those obtained with the exterior wall vents closed because the buildup of pressures in the floor space with the wall vents closed is relieved when they are opened.

Air velocities at the vertical centerline of the open stair door on the second floor with the stairshaft pressurization off are given in Table 7. When the stair door on the first floor

TABLE 7
Air Velocities at Open Stair Door on the Second Floor Caused by Stack Action

Outside Temperature—30°F (-1°C)
Wind—12 mph (19 kmh) south

	Vertical Centerline Air Velocity at Open Stair Door on Second Floor, fpm (m/s)		
Height ft (m)	**A Stair Door on 1st Floor Open**	**B Outside Wall Vents on 2d Floor Open**	**A & B**
6.5 (1.98)	0 (0.00)	−31 (−0.16)	−49 (−0.25)
5.5 (1.67)	41 (0.21)	−21 (−0.11)	0 (0.00)
4.5 (1.37)	45 (0.23)	55 (0.28)	39 (0.20)
3.5 (1.10)	81 (0.41)	106 (0.54)	47 (0.24)
2.5 (0.76)	69 (0.35)	124 (0.63)	55 (0.28)
1.5 (0.46)	112 (0.57)	148 (0.75)	88 (0.45)
0.5 (0.15)	112 (0.57)	128 (0.65)	84 (0.43)

was opened, the air velocities into the second floor varied from 112 fpm (0.57 m/s) near the bottom to 0 fpm (0 m/s) near the top of the door opening. When the stair door on the first floor was closed and the outside wall vents on the second floor were opened, air flowed from the stairshaft into the floor space from the bottom to about the 5 ft (1.5 m) level and air flowed in the reverse direction above this level. When both the stair door on the first floor and the exterior wall vents on the second floor were opened, air flowed from the stairshaft to the floor space for almost the full height of the stair door opening with reversal of the flow direction only at the 6.5 ft (1.98 m) level.

Opening the stair door on the first floor in summer with the temperature higher outside than inside would have the reverse effect on the pressure differences across the stair doors to those in winter, but the influence of stack action would be less because of the lower inside-to-outside temperature differences in summer than in winter.

SUMMARY

The stair pressurization systems were tested with a fire temperature of 840°F (450°C) with the exterior wall vents closed and open, and with a fire temperature of 1200°F (650°C) and the exterior wall vents open. The following is a summary of observations:

1. With the fire floor (second floor) unvented and under summer conditions, the stairshaft was contaminated with smoke for all test stair pressurization systems when the stair doors on the first and second floors were open.

2. With the fire floor vented by exterior wall vents and under summer conditions, the stairshaft was contaminated with smoke for all test stair pressurization systems when three or more stair doors, including the one of the fire floor, were open.

3. Stack action during winter assisted the stair pressurization systems when the exit stair door was opened to the outdoors. All tested stair pressurization systems performed better under winter than under summer conditions.

4. The performance of the stair pressurization system with exit door relief and a supply air rate of 17,800 cfm (8.4 m^3/s) was slightly less than that of the stair pressurization system with barometric dampers and a supply air rate of 28,000 cfm (13.2 m^3/s) and those of the stair pressurization system with feedback control and a maximum supply air rate of about 30,000 cfm (14.2 m^3/s).

5. The response time of the stair pressurization systems with feedback control were long enough so that momentary smoke contamination of the stairshaft can be expected with a drop in pressurization when a stair door is opened. The response time of the feedback control with a variable-speed drive fan was slightly shorter than that of the fan bypass.

6. The minimum observed average air velocities during the nonfire tests of Phase 3, which corresponded to no smoke backflow during the fire tests, were 260 fpm (1.31 m/s) for a fire temperature of 840°F (450°C) under summer conditions with the exterior wall vents open and stair doors open on floors 1 and 2 (Table 6) and 281 fpm (1.43 m/s) for a fire temperature of 1200°F (650°C) under the winter condition with the exterior wall vents open and stair doors open on floors 1, 2, 3, and 8 (Table 4). These values give only an indication of the critical air velocities for the two fire temperatures with the outside wall vents open. Values for cases with the outside wall vents closed were not available because smoke backflow occurred for all conditions tested. Specific studies on determining critical air velocities to prevent smoke backflow are required to investigate the effect of such factors as number of open stair doors, position of the exterior wall vents, and fire temperature.

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