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Stair Pressurization Systems for Smoke Control: Design Considerations

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ABSTRACT

Literature on the various types of pressurization systems, stair use during evacuation, and code requirements was reviewed and summarized. Non-fire and fire tests were conducted in the 10-story experimental fire tower of the National Fire Laboratory of the National Research Council of Canada. The flow resistances of an open stair door at various angles were measured. Under fire conditions, the vertical profiles of pressure differences across the stairshaft wall and those of the velocity pressure at the stair door opening were measured. With the stairshaft pressurized, the critical velocities required to prevent smoke backflow at the stair door opening on the fire floor were determined and compared with the calculated values for various fire temperatures.

INTRODUCTION

Various methods for protecting stairwells from smoke intrusion during a fire have evolved over the past several years. The one used most often in North America is the stairshaft pressurization system. Designing such systems is complicated because an intermittent loss of effective pressurization occurs when occupants enter and leave the stairs during evacuation. Therefore, the pressurization system should have a supply air fan with sufficient capacity to provide effective pressurization to prevent smoke entry when doors are open and a means of preventing overpressurization, which can make door opening difficult when all doors are closed. To prevent such overpressures, the design concepts of barometric damper relief, feedback control with fan bypass, variable-speed or variable-pitch fan, and exit door relief have been developed. Although many such systems have been built, it is not known at present to what extent they are effective. An ASHRAE research project, RP-559, was undertaken with the objective of assessing these systems and developing design recommendations for various methods of overpressure relief. It involves (1) a literature review, (2) field tests, (3) full-scale fire tests, and (4) a design analysis.

In this paper the results of studies conducted during the first phase of the project are presented. They involved a literature review of stair pressurization systems, stair use during evacuation, and code requirements. They also involved tests in the experimental fire tower to determine flow coefficients for various angles of door opening, with and without people, and critical air velocities to prevent smoke backflow at an open stair door for various fire temperatures.

LITERATURE REVIEW

Pressurization Systems

The stair pressurization systems reviewed can be categorized as systems with and without lobbies. The former provide an additional door to restrict loss of pressurization air, while the lobby serves as a staging area for firefighters or a temporary holding areas for occupants. The lobby, the stairshaft, or both can be pressurized or, in some instances, these spaces can also be exhausted. Design guidelines for stairshafts with lobbies have been published by Hobson and Stewart (1973) and for stairshafts without lobbies by Klote and Fothergill (1983) and Thornberry (1982). Descriptions and tests of stairshaft protection systems with lobbies are given by Butcher et al. (1969, 1976), Cottle et al. (1971), Degenkolb (1971), and Tamura (1980). In North America, pressurization systems for stairshafts without lobbies are more prevalent than systems for stairshafts with lobbies; this paper is, therefore, concerned with the former.

The early stair pressurization systems in buildings were of the single-injection type with a fan usually located at the top of the building. Such systems and their tests are described by Fung (1973) and Klote (1980). Tests of these systems with the fan sized to pressurize a stairshaft with the exit door open (Deccico 1973; Cresci 1973; Coplan 1973; Tamura 1974) revealed that pressure differences across the stair doors near the point of injection can be excessive, making these difficult to open. Pressure differences far from the point of injection can be minimal and may fail to prevent smoke infiltration. This variation in pressurization caused by the flow resistance in the stairwell (Achakji and Tamura 1988; Cresci 1973; Tamura 1974) led to the design of a stairwell pressurization system with multiple injection points. Examples of such systems are described in papers by Dias (1978), Erdelyi (1973), and Fothergill and Hedsten (1980).

The pressures inside the stairshaft should be controlled to prevent under- or overpressurization of the stairshaft when stair doors are used during a fire. Some of the methods being used to achieve pressure control are: a supply air fan and relief vents in the stairshaft walls; a sup-

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ply air fan with variable-speed, variable-pitch blades; or a supply air fan with supply air bypass dampers, all controlled by a static pressure sensor in the stairshaft. The supply air damper of the system described by Dias (1978) is controlled from a static pressure sensor to maintain a specified pressure difference across the wall of the stairshaft. Information on such a pressure control system for smoke control is given by Shavit (1983, 1988).

Evacuation

A means of egress is designed to evacuate occupants from endangered areas as quickly and efficiently as possible. It is based on such factors as number of occupants, occupant densities, and occupant characteristics (such as physical size, need for personal space, and walking speed) to meet the desired flow rates for efficient evacuation (*Fire Protection Handbook* 1986). A number of evacuation drills have been conducted in multi-story buildings to develop models for predicting egress times and to assess the problems encountered during evacuation (Kagawa et al. 1985; Kendik 1986; MacLennan 1985; Melinek 1975; Pauls 1975, 1977, 1980a, and 1980b). The two methods of planned evacuation are uncontrolled total evacuation, where building occupants attempt to evacuate at the same time, and controlled selective evacuation, where the building occupants evacuate under instruction from a public address system. The results of an evacuation drill using each method are compared by Pauls (1980a).

Of particular interest for the design of stairshaft pressurization and for code requirements is the operation of stair doors during evacuation, which can cause loss of pressurization and, hence, the capability of the system to prevent smoke from infiltrating the stairshaft. Operation of stair doors can vary with the method of evacuation, occupant density, type of building occupancy, firefighting operation, and other factors. Under uncontrolled total evacuation, all stair doors can be open for a short time soon after sounding of an alarm except for the doors on the fire and exit floors, which can be open for a prolonged period. During controlled selective evacuation, a few doors other than those on the fire and exit floors may be open for a short period at any given time. Evacuation in a building of residential occupancy can be prolonged, as reported by Bryan (1983) on the MGM Grand Hotel fire. Because of low occupant density, doors are likely to be open for considerably shorter periods in hotels and apartments compared to those in office buildings.

The literature on evacuation was reviewed to assist in scheduling of door operation for testing of stair pressurization systems to be conducted during the second and third phases of the research project.

The critical velocities required to prevent smoke backflow in a corridor has been developed by Thomas (1970) in terms of energy release rate into the corridor. Also, Shaw and Whyte (1974) dealt with the velocity required to prevent contaminated air from moving through an open doorway in the presence of small temperature differences. Klote and Fothergill (1983) discussed these references in the ASHRAE smoke control design manual.

Codes

The requirements in the building codes for stairshaft pressurization systems include supply air rates, required minimum and allowable maximum pressurization, and minimum air velocity through doors for number and location of open stair doors.

In Australian Standard 1668, Part 1 (1979), pressure differences with all doors closed are not to exceed 0.20 in of water (50 Pa) or the force required to open the door at the door knob is not to exceed 25 lbs (110 N). With three doors open, the airflow velocity from the stairshaft is to be not less than 200 fpm (1 m/s), averaged over the full area of the door opening. The pressurization system is to be automatically controlled such that when operation of doors or other factors cause significant variations in airflow and pressure differences, the above conditions are to be restored as soon as practicable.

In BOCA (1984), for buildings with a fire suppression system throughout, the smoke-proof enclosures may be eliminated provided that all interior stairshafts are pressurized to a minimum of 0.15 in of water (37.3 Pa) and a maximum of 0.35 in of water (87 Pa) in the shaft relative to the building with all stair doors closed.

British Standard Institution BS 5588:Part 4 (1978) recommends a simple lobby to reduce the effect of an open door to the pressurized stairshaft. The required pressurization is 0.20 in of water (50 Pa).

The City of New York Local Law No. 84 (1979) requires a supply air rate of at least 24,000 cfm (11.33 m^3/s) plus 200 cfm (0.094 m^3/s) per floor. The maximum velocity of air supplied at the openings into the stairs is 3000 fpm (15.2 m/s) at its point of discharge within the stairshaft. The maximum permissible pressure difference between the stair and the floor space is 0.40 in of water (100 Pa) with the door open or closed. The minimum permissible pressure difference is 0.10 in of water (25 Pa) when all stair doors are closed or not less than 0.05 in of water (0.125 Pa) when any three doors are open. As an alternative to the maintenance of 0.05 in of water (0.125 Pa), a minimum average velocity of 400 fpm (2 m/s) through the stair door with any three doors open is to be maintained. The maximum velocity permitted through a single open door with all other doors closed is 2000 fpm (10.2 m/s). The door-opening force at the door knob is limited to 25 lbs (110 N) using mechanical assistance as required.

The Supplement to the National Building Code of Canada (1985), Chapter 3, "Measures for Fire Safety in High Buildings," recommends a supply air rate of 10,000 cfm (4.72 m^3/s) plus 200 cfm (0.094 m^3/s) for every door opening into the stairshaft. The exit door to outdoors in each stairshaft is to be held open when the supply air fan is initiated.

The Standard Building Code (1985) specifies smokeproof enclosures. They may be omitted for buildings with a complete sprinkler system provided that all required stairways are equipped with a dampered relief opening at the top and supplied mechanically with sufficient air to discharge a minimum of 2500 cfm (1.18 m/s) through the relief opening while maintaining a minimum positive pressure of 0.15 in of water (37.3 Pa) relative to atmospheric pressure with all stair doors closed.

Figure 1 *Experimental fire tower*

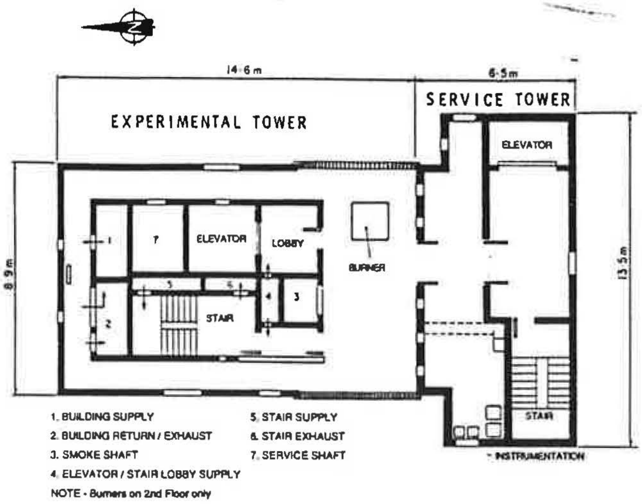


Figure 2 *Plan of the experimental fire tower*

TEST PROCEDURE

The research project is concerned with the performance of pressurization systems with overpressure relief features. The first phase requires preliminary testing of the airflow characteristic through an open stair door and determination of the air velocity required at the stair door opening on the fire floor to prevent smoke backflow into the stairshaft. In addition, tests were conducted to determine the number of points required to measure the airflow rate through an open stair door by a hot-wire anemometer traverse.

Tests were conducted in the 10-story experimental fire tower of the National Fire Laboratory of the National Research Council of Canada, located near Ottawa, Ontario (Figure 1). The plan view of the tower is shown in Figure 2. The tower contains all the shafts and other features necessary to simulate air and smoke movement patterns in a typical multi-story building, including elevator, stair, smoke exhaust, service, supply, and return air shafts. Two propane gas burner sets, each capable of producing heat at an output of 8.5 million Btu/h (2.5 MW), are located in the second-floor burn area. The leakage areas of the experimental fire tower were set for a building with average air tightness and a floor area of 9700 ft^2 (900 m^2), or seven times that of the experimental tower.

The walls of the stairshaft are constructed of 8-in (200-mm) poured concrete. The stair door is 3 ft by 7 ft (0.914 m by 2.13 m). The leakage area of each stair door was set to be 0.25 ft^2 (0.023 m^2); that for the shaft wall for each floor (0.04 ft^2 [0.004 m^2]) was represented by an orifice located in the shaft wall on the corridor side 5 ft (1.52 m) above floor level. The supply air shaft is adjacent to the stairshaft (see Figure 2) with a supply air opening on each floor to permit injection of supply air on all floors or only at the top or the bottom of the stairshaft. The supply air duct system is connected to a centrifugal fan with a capacity of 38,000 cfm at 2.6 in of water (18 m^3/s at 650 Pa) and with a variable-speed drive.

Three tests related to the stair door opening were conducted. They were:

- calibration of hot-wire anemometer traverse for 9, 15, and 21 points;
- determining flow coefficients of stair door opening at various angles, with and without people; and
- determining critical velocities to prevent smoke backflow on the fire floor.

For these tests, the lobbies associated with the stairshaft were effectively removed by taking out the lobby walls and leaving their doors open.

The airflow rates through the stair door opening were measured at the airflow measuring station, which was located downstream of the fan inside a metal duct 3.6 ft by 3.6 ft (1.10 m by 1.10 m) connected to the bottom of the vertical supply air shaft adjacent to the stairshaft. The airflow measuring station consisted 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. The airflow measuring station was calibrated using a 42-point pitot traverse downstream of the measuring station and also was checked with the tracer gas dilution technique (Owen 1967) using CO as the tracer gas. The results of the pitot traverse and the tracer gas measurements were within 5% of each other.

The ductwork downstream of the measuring station and the walls of the stairshaft, including all stair doors, were sealed either by caulking or by taping the cracks and joints. The air leakage rates of the sealed duct and the walls of the stairshaft for the full height were measured at pressure differences across the walls of the stairshaft of 0.10, 0.20, and 0.30 in of water (25, 50, and 75 Pa). They were low, with a leakage rate of 300 cfm (141 L/s) at 0.30 in of water (75 Pa), which represents a total equivalent orifice leakage area of 0.22 ft^2 (0.020 m^2), or about 1% of the open area of the test stair door. The corrected airflow rates through an open stair door during the tests were obtained by subtracting the air leakage rate of the duct/stair system from the airflow rate obtained at the measuring station.

Figure 3 *Velocity pressure tubes at open stair door*

Airflow rates below 2000 cfm (940 L/s) were measured with an orifice of 1.5 ft (0.48 m) in a metal plate inserted in the duct upstream of the airflow measuring station. All tests were conducted with the duct/stair system sealed, except for the open stair door on the test floor.

Hot Wire Anemometer Traverse

In order to determine the number of measuring points required to make a reasonable estimate of the average velocities or the airflow rate through a door opening, hot wire anemometer traverses were conducted with the stair door open at 90° on the fifth floor of the experimental fire tower. Air velocities were measured at 9, 15, and 21 points, with each point in the middle of equally subdivided areas. Each set of traverses was made at four airflow rates, ranging from 3000 to 10,000 cfm (1.42 to 4.72 m^3/s), measured at the airflow measuring station in the supply air duct. The supply air was injected at the bottom of the stairshaft and was allowed to flow up the stairshaft and out through the open stair door on the fifth floor.

Flow Resistance of Stair Door Opening

Flow through a door opening can be expressed as

$$Q = KA[2g_c\rho(p_1 - p_2)]^{1/2} \qquad (1)$$

where

Q = volume flow rate, ft^3/s (m^3/s)
K = flow coefficient, dimensionless
A = area of opening, ft^2 (m^2)
g_c = gravitational conversion factor, 32.174 $lb_m/lb_f \cdot ft/s^2$ (9.806 m/s^2)
ρ = density of fluid, lb_m/ft^3 (kg/m^3)
$p_1 - p_2$ = pressure difference across the stair door opening, lb_f/ft^2 (Pa)

K is a constant made up of a contraction coefficient, a friction loss coefficient, and an approach factor.

The tests to determine the flow coefficients were conducted on the fifth floor of the experimental fire tower. They involved measuring the pressure drop across the stair door with a diaphragm-type magnetic reluctance pressure transducer and the flow rates at the airflow measuring station, and calculating the flow coefficient, *K*, using Equation 1. For all calculations, *A* was taken as 21 ft^2 (1.95 m^2).

For the first series of tests, without people, the supply air was injected at the bottom of the stairshaft and allowed to flow up to the stair door opening on the fifth floor. The supply air rates were adjusted to give a pressure difference of 0.10, 0.15, or 0.20 in of water (25, 37.5, or 50 Pa) across the stair door opening for door angles of 90°, 70°, 60°, 23°, and 5°. This series of tests was repeated with supply air injected inside the stairshaft on floors 1, 3, 5, 7, and 10.

The second series of tests was conducted with people in the doorway, with the door open at the 60° angle to approximate the position used when a door is opened to enter a stairshaft. The supply air was injected at the bottom of the stairwell. The test subjects were as follows:

Person	**Physical Characteristics**
A	6 ft 1 in (1.84 m), 160 lb (72.6 kg)
B	5 ft 9 in (1.75 m), 170 lb (77.2 kg)
C	5 ft 7 in (1.70 m), 150 lb (68.1 kg)
D	5 ft 0 in (1.52 m), person C crouched

A number of 1 ft (0.305 m) diameter cardboard cylinders of heights corresponding to the test subjects were used as well for the tests. Tests were conducted with each person standing at the door opening or with two people placed 1 ft (0.305 m) on either side of the door opening. These tests were repeated with the cardboard cylinders.

Critical Velocity

The tests to determine the critical velocity to prevent smoke backflow at the stair door opening were conducted on the second floor with the gas burners. Static pressure taps to measure the pressure differences across the wall of the stairshaft on the corridor side were installed at 1.3 ft, 7 ft, and 10 ft (0.396 m, 2.183 m, and 3.048 m) above floor level. Thermocouples to measure temperatures inside and outside the stairshaft were installed at these levels.

Bi-directional gas velocity probes (McCaffrey and Heskestad 1976) were installed along with thermocouples in front of and at the vertical centerline of the stair door opening at 1.33 ft, 2.66 ft, 4.00 ft, 5.33 ft, and 6.66 ft (0.405 m, 0.811 m, 1.220 m, 1.625 m, and 2.032 m) above floor level (Figure 3).

Measurements were made under the following test conditions on the second (fire) floor with the supply air duct/stairshaft system sealed as before.

1. With the stair door closed and without stairshaft pressurization, tests were conducted at fire temperatures

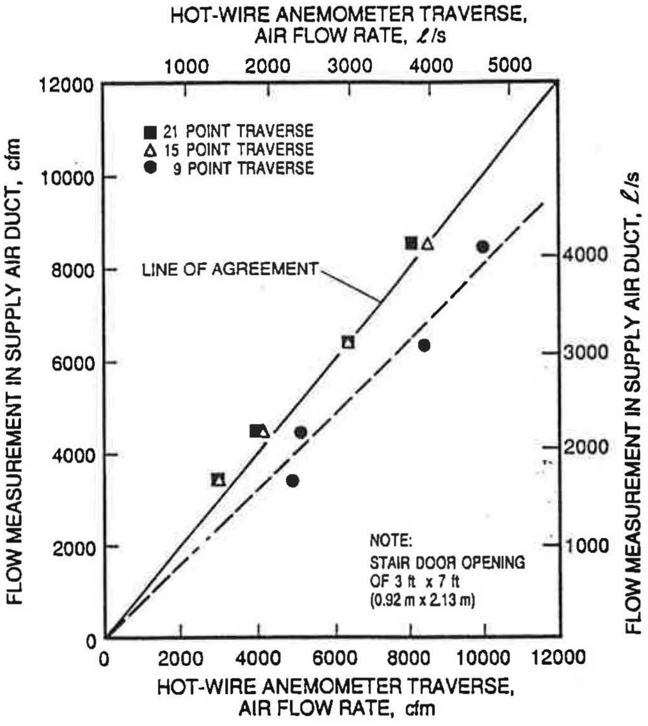


Figure 4 *Comparison of airflow measurements at stair door opening using 9, 15, and 21 point hot-wire anemometer traverse*

of 570°F (300°C) and 1300°F (700°C) and with the outside wall vents of 10 ft^2 (0.929 m^2) closed and also with them open to simulate broken windows.

The fire temperatures were measured directly above the burners and just below the ceiling and were controlled at the test temperatures by adjusting the propane gas flow rate. The tests were conducted to obtain vertical profiles of pressure differences across the stairshaft wall caused by the fire.

2. With the stair door open at 90° and without stairshaft pressurization, tests were conducted at fire temperatures of 570°F (300°C) and 1300°F (700°C) and with the outside wall vents closed and also with them open. They were conducted to obtain the vertical profiles of pressure differences across the stairshaft wall and the velocity pressures at the stair door opening.

3. With the stair door open at 90° and with the stairshaft pressurized with bottom injection, tests were conducted at a fire temperature of 570°F (300°C); the outside wall vents were closed. The supply air rate was adjusted to the point of no gas backflow into the stairshaft and the rate recorded. The test was repeated with the outside wall vents open.

4. With the stair door open at 90° and with the stairshaft pressurized with bottom injection, tests were conducted at a fire temperature of 1075°F (600°C); the outside wall vents on the second floor were open, as the windows are likely to break at this temperature. The supply air rate to the stairshaft was adjusted to the point of no gas backflow at the stair door opening.

5. Same as Test 3, except that the stair door was in the 60° open position.

6. Same as Test 4, except that the stair door was in the 60° open position.

TABLE 1
Flow Coefficient (K) for a Stair Door Opening with People and with Body Simulator

Door angle—60°
Supply air to stairshaft—bottom injection
Test stair door on fifth floor of experimental fire tower

Person	K	Body Simulator	K
—	0.593	—	0.593
A	0.509	A′	0.533
B	0.504	B′	0.534
C	0.514	—	—
D	0.524	D′	0.545
B + C	0.465	—	—
—	—	A′ + A′	0.487
		B′ + B′	0.498

Note:
A Male, 6 ft 1 in (1.84 m), 160 lb (72.6 kg)
B Male, 5 ft 9 in (1.75 m), 170 lb (77.2 kg)
C Male, 5 ft 7 in (1.70 m), 150 lb (68.1 kg)
D Male, 5 ft 0 in (1.52 m), person C crouched
A′ Cardboard cylinder, 6 ft 0 in (1.83 m), 1 ft (0.305 m) diam.
B′ Cardboard cylinder, 5 ft 9 in (1.75 m), 1 ft (0.305 m) diam.
D′ Cardboard cylinder, 5 ft 0 in (1.52 m), 1 ft (0.305 m) diam.

The point of smoke backflow while the supply air rate was being adjusted was determined by observing the movement of 2 in (51 mm) long thin plastic strips placed along the top of the door with their ends exposed 1 in (25.4 mm) in the gas flow.

RESULTS AND DISCUSSIONS

Hot Wire Anemometer Traverse

The results of the 9-, 15-, and 21-point traverses are shown in Figure 4. With the airflow in one direction through the door opening, the airflow rates were calculated by multiplying the average air velocity by the area of the door opening. These were plotted against the rates measured at the airflow measuring station in the supply air duct. The airflow rates obtained using the 9-point traverse were about 20% higher, while the airflow rates obtained with the 15- and 21-point traverses agreed with those measured at the airflow measuring station. Because the difference in time taken to conduct a 15- or a 21-point traverse is minimal, the 21-point traverse is recommended for a standard-sized door when testing a stair pressurization system in the field.

Flow Resistance of Stair Door Opening

For each test condition, the value of the flow coefficient, K, was calculated for pressure differences of 0.05, 0.10, and 0.15 in of water (12.5, 25, and 37.5 Pa). The value of K was relatively constant and within 2% of its average value for the range of test pressure differences; hence, only the average values are presented in Table 1.

The values of K for various door angles for both bottom air injection and multiple injection (floors 1, 3, 5, 7, and 10) are shown in Figure 5. The angle of 5° is intended to represent an opening with a 2.5 in (63 mm) diameter fire hose in a doorway, 60° an opening when a person is passing through a doorway, and 90° a fully open door. The curve, fitted to the data, is relatively smooth for multiple injection, with values of 0.06, 0.65, and 0.73 for 5°, 60°, and 90°, respectively. The values obtained with bottom injec-

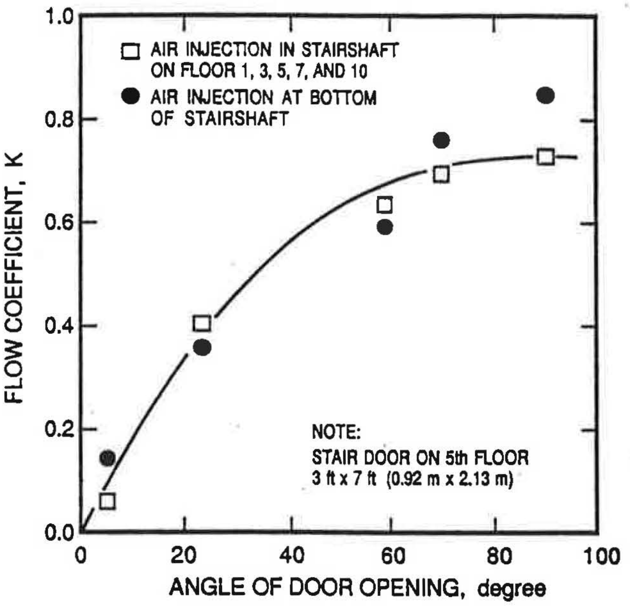


Figure 5 *Flow coefficients for a stair door at various angles of opening*

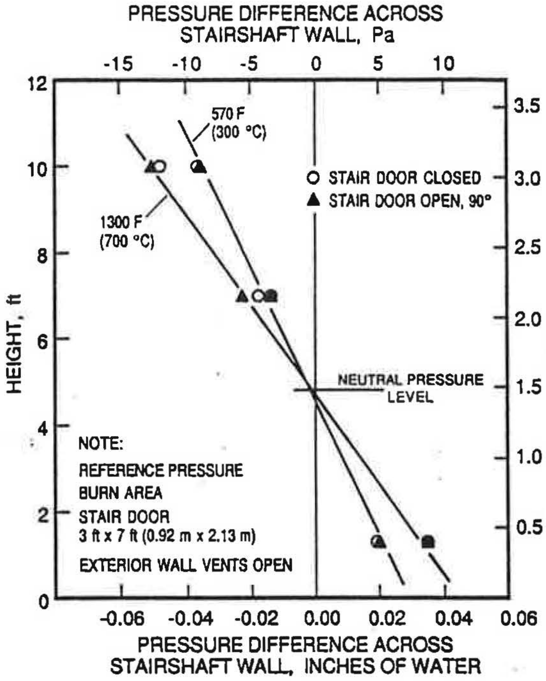


Figure 6 *Pressure difference across stairshaft wall with stair door open and closed on fire floor*

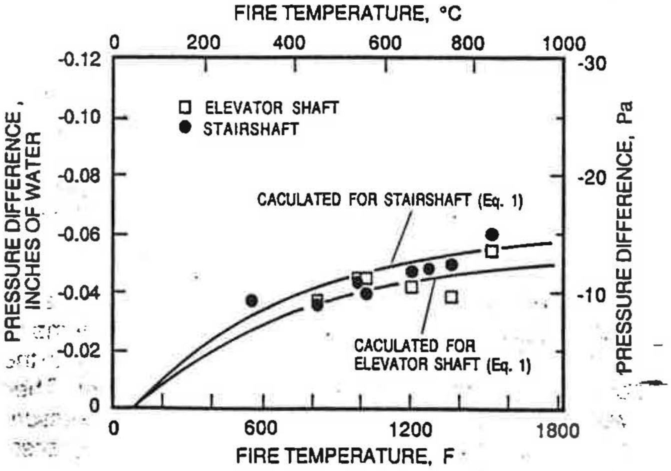


Figure 7 *Pressure difference across stairshaft wall and elevator shaft wall for various fire temperatures (pressure difference measured 10 ft [3.08 m] above 2nd floor level)*

tion are above and below this curve; the corresponding values are 0.14, 0.59, and 0.85. The values of *K* were apparently affected by the method of air injection, which affected the approach and entry conditions of the airflow at the door opening.

The values of *K* with people or body simulators in the door opening (door open at 60°) with bottom injection of supply air to the stairshaft are given in Table 1. Without anybody in the doorway, *K* was 0.59; with one person, *K* varied from 0.51 to 0.52 for heights varying from 5 ft (1.52 m) to 6 ft, 1 in (1.84 m), i.e., a reduction in *K* of 12% to 13%. With the body simulators of 1 ft (0.3048 m) diameter, the reduction was 8% to 10%. With a person or body simulator on both sides of the door opening, the reductions in *K* varied from 16% to 21%.

The data obtained from these tests give some indication of the effect of people on *K* value and can be used in computer modeling for studying the performance of stair pressurization systems. The body simulators can be useful for fire tests.

Critical Velocity

In this paper the average air velocity at the stair door opening on the fire floor required to prevent smoke from entering the stairshaft is referred to as the critical velocity to prevent smoke backflow. It is calculated by dividing the airflow rate that is just sufficient to prevent smoke backflow by the area of the stair door opening.

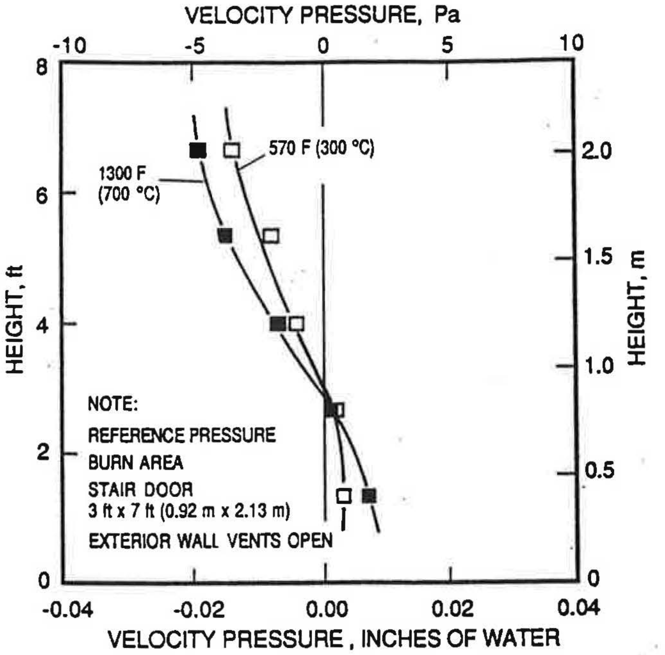
Figure 6 shows the pressure difference across the wall of the stairshaft (stairshaft pressure − burn area pressure) without stairshaft pressurization; that is, the pressure difference caused only by the buoyancy force for fire temperatures of 570°F (300°C) and 1300°F (700°C). The pressure differences are about the same, whether the stair door is closed or open. The neutral pressure level is located 4.80 ft (1.46 m) above floor level.

Pressure differences across the walls of the stair and elevator shaft were measured at the 10 ft (3.048 m) level in a previous study on fire pressures by Tamura and Klote (1988). These previous values, along with the pressure differences measured in this study, are plotted against fire temperatures in Figure 7. The neutral pressure level of the elevator shaft is located at 5.58 ft (1.7 m) above floor level. The pressure differences were calculated using the following buoyancy equation:

$$P_s - P_f = gh\rho_f(T_f - T_i) / T_i \qquad (2)$$

where

$P_s - P_f$ = pressure difference across the shaft wall
g = gravitational constant
h = distance from the neutral pressure level



NOTE:
REFERENCE PRESSURE
BURN AREA
STAIR DOOR
3 ft x 7 ft (0.92 m x 2.13 m)
EXTERIOR WALL VENTS OPEN

Figure 8 *Centerline velocity pressure profile at open stair door (90°) on fire floor*

ρ = gas density
T = temperature

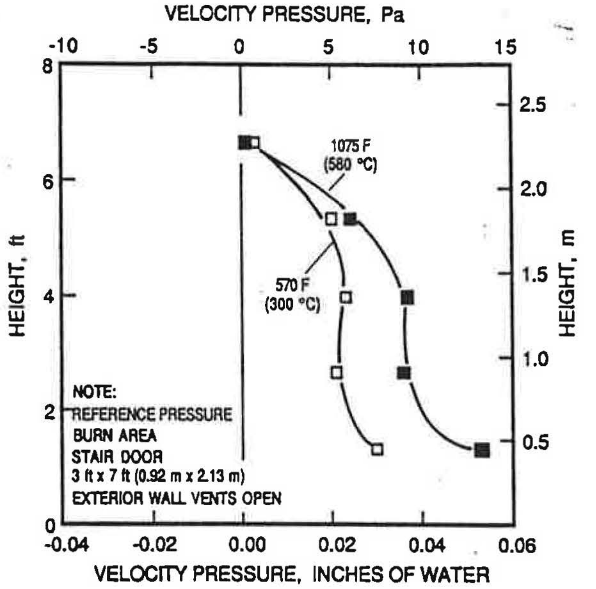
Subscripts

s = shaft
i = outside the fire compartment
f = fire compartment

The calculated values for the stairshaft and elevator shaft, using their respective neutral pressure levels, are also shown in Figure 7. Because of the lower neutral pressure level, the pressure differences across the walls of the stairshaft are higher than those of the elevator shaft. For both shafts the temperatures near the ceiling above the gas burners (Figure 2) were used in the calculations, although spatially the temperatures in the burn area varied greatly. Using this temperature in Equation 1, which assumes a uniform space air temperature, however, gave a good estimate of the pressure differences across the walls of both elevator shaft and stairshaft.

Figure 8 shows the centerline velocity pressure profiles at the stair door opening without stairshaft pressurization for fire temperatures of 570°F (300°C) and 1300°F (700°C). The velocity pressures referenced to the burn area pressure at 6.66 ft (2.03 m) were −0.014 in of water (-3.5 Pa) for a fire temperature of 570°F (300°C) and −0.019 in of water (−4.7 Pa) for a fire temperature of 1300°F (700°C). These values compare with pressure differences measured across the stairshaft wall at the 7 ft (2.13 m) level of −0.014 in of water (−3.5 Pa) and −0.021 in of water (−5.2 Pa), respectively (Figure 6).

With stairshaft pressurization, the flow rate was increased until no backflow was observed. At a stair door opening of 900, when the velocity pressure was balanced at the top of the door opening, the direction of flow was from the stairshaft into the burn area for the full height of the stair door (Figure 9) and, hence, smoke backflow was prevented. During tests this was verified visually by running a smoke pencil for the full height of the opening. The flow rates required to prevent smoke backflow were 7380 cfm (3.48 m3/s) for a fire temperature of 570°F (300°C) with the exterior wall vents either closed or open and 9200 cfm (4.34 m^3/s) for a fire temperature of 1076°F (580°C) with the exterior wall vents open (the temperature of 1300°F (700°C) was not reached because of cooling effect of pressurization air in the burn area). The corresponding critical velocities were calculated to be 350 fpm (1.78 m/s) and 438 fpm (2.22 m/s), respectively.



NOTE:
REFERENCE PRESSURE
BURN AREA
STAIR DOOR
3 ft x 7 ft (0.92 m x 2.13 m)
EXTERIOR WALL VENTS OPEN

Figure 9 *Centerline velocity pressure on fire floor with stairshaft pressurized to prevent smoke backflow*

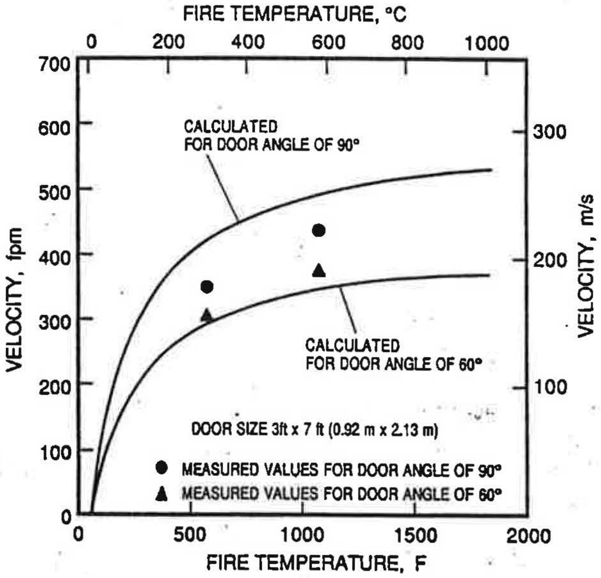


Figure 10 *Critical velocity vs. fire temperature for door open angle of 60° and 90°*

At a stair door opening of 60°, the critical velocities were 306 fpm (1.55 m/s) and 377 fpm (1.92 m/s) for fire temperatures of 570°F (300°C) and 1076°F (580°C), respectively.

From the above, the critical velocity can be determined by: calculating the pressure difference caused by fire at the top of the door opening using Equation 2, calculating the amount of pressurization air required to prevent smoke backflow using Equation 1 with the appropriate value of flow coefficient from Figure 5, and calculating the critical velocity by dividing this flow rate by the area of the stair door opening.

The calculated and measured values of critical velocity for various fire temperatures for the test stair door are given in Figure 10 for door angles of 60° and 90°. The values on the graph show that the calculation overestimates the measured values for the 90° door angle, whereas the calculated values are in good agreement with the measured values for the 60° door angle.

SUMMARY

There is little information in the literature on the performance of stairshaft pressurization systems with overpressure relief features to deal with door operation during a fire. The number of doors open at a given time and the significance in terms of smoke contamination depend mainly on the type of evacuation (whether uncontrolled total or controlled selective), building use, and occupant density. Some codes specify the open door condition to which a stair pressurization system must maintain the required pressure. Others specify the air velocity required at the door opening. Most codes specify the required amount of minimum and maximum pressurization. These factors must be considered in setting procedures for testing stairshaft pressurization systems to be conducted in the second and third phases of this research project.

From tests in the 10-story experimental fire tower, a 21-point velocity traverse was found to give a good estimate of the average air velocity for calculating the rate of airflow through a standard-sized door opening. Although a 15-point traverse gave just as good an agreement in the tower test, it is worthwhile to take the extra time to conduct a 21-point traverse because of the various air inlet and door configurations encountered in buildings. Tests were conducted to determine the flow coefficients for door opening at various angles and with and without people. Tests were also conducted to determine the critical velocities to prevent smoke backflow at the stair door opening at various fire temperatures. The calculated values were in good agreement with the measured values for a door angle of 60°, but they were higher than the measured values for a door angle of 90° (Figure 10).

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