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DETERMINATION OF CRITICAL AIR VELOCITIES TO PREVENT SMOKE BACKFLOW AT A STAIR DOOR OPENING ON THE FIRE FLOOR—660 RP*

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ABSTRACT

Tests to determine air velocities to prevent smoke backflow were conducted in the ten-story experimental fire tower of the National Fire Laboratory of the National Research Council of Canada. They were measured at the stair door opening on the fire floor for burn temperatures ranging from 150°F (65°C) to 1200°F (650°C) at an increment of 150°F (83°C). The critical velocities ranged from 124 feet per minute (ft/min) (0.63 m/s) at 150°F (65°C) to 460 ft/min (2.34 m/s) at 1200°F (650°C). Some of the other parameters investigated resulted in decreases in the critical air velocity. These included venting either by exterior wall vents or an exhaust fan, and opening stair doors in addition to the one on the fire floor. Reducing the angle of door opening from 90° to 30° decreased the effective critical air velocities, compared to those at an area of the door opening at 90°, by 50 percent. There was no noticeable effect on critical air velocities when the method of pressurization of the stairshaft was changed from multiple injection to bottom injection.

During a fire, stairshafts can become contaminated with smoke that can endanger the lives of occupants attempting to leave the building. Smoke contamination of the stairshafts can be prevented by mechanically pressurizing the stairshaft with outdoor air. Various stair pressurization systems for protecting stairwells from smoke infiltration have evolved over the past several years [1]. These systems are designed to maintain sufficient pressurization inside the stairshaft so that its pressures are higher than those in the fire floor caused by fire and other forces

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when all stair doors are closed. When stair doors are open, these systems are also designed to provide sufficient air velocities to prevent smoke backflow at the stair door opening on the fire floor. The objective of this project was to determine the critical average air velocities required to prevent smoke backflow at the stair door opening for various fire conditions.

The critical air velocities required to prevent smoke backflow in a corridor were developed by Thomas in terms of energy release rate into the corridor [2]. Also, Shaw and Whyte dealt with the air velocity required to prevent contaminated air from moving through an open doorway in the presence of small temperature differences [3]. Heskestad and Spaulding dealt with airflow required at wall and ceiling apertures to prevent escape of fire smoke [4]. All these tests were conducted in the laboratory.

In this study, tests were conducted in the experimental fire tower simulating a typical multi-story open floor plan building to investigate various parameters affecting critical air velocities. The parameters investigated were fire temperature, venting of the fire floor with exterior wall vents and an exhaust fan, angle of stair door opening, number of open stair doors, and method of air injection for stair pressurization.

TEST PROCEDURE

The plan view of the ten-story experimental fire tower of the National Fire Laboratory of the National Research Council of Canada is shown in Figure 1. The tower contains vertical shafts such as those found in a typical multi-story building, including elevator, stair, smoke exhaust, service, supply, and return air shafts. The leakage areas of the experimental fire tower were set for a building with average air tightnesses and a floor area of 9700 ft^2 (900 m^2), or seven times that of the experimental fire tower.

The walls of the stairshaft are constructed of eight inch (200 mm) poured concrete. Each stair door is three feet by seven feet (0.914 m × by 2.13 m). The leakage area of each stair door is 0.25 ft^2 (0.023 m^2) and the leakage area for the shaft wall for each floor is 0.03 ft^2 (0.004 m^2), represented by an orifice located in the shaft wall on the corridor side five feet (1.52 m) above floor level. The supply air shaft is adjacent to the stairshaft (see Figure 1), 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 shaft is connected by ductwork to a centrifugal fan with a capacity of 38,000 cfm at 2.6 inches of water (18 m^3/s at 650 Pa) and with a variable-speed drive.

For a supply air flow rate of more than 2000 cfm (940 L/s), the flow rate is measured at a measuring station located downstream of the fan inside a metal duct. The airflow measuring station consisted of multi-point self-averaging total pressure tubes and their associated static pressure taps and an air straightener of honeycomb panel located immediately upstream of the averaging tubes. Airflow

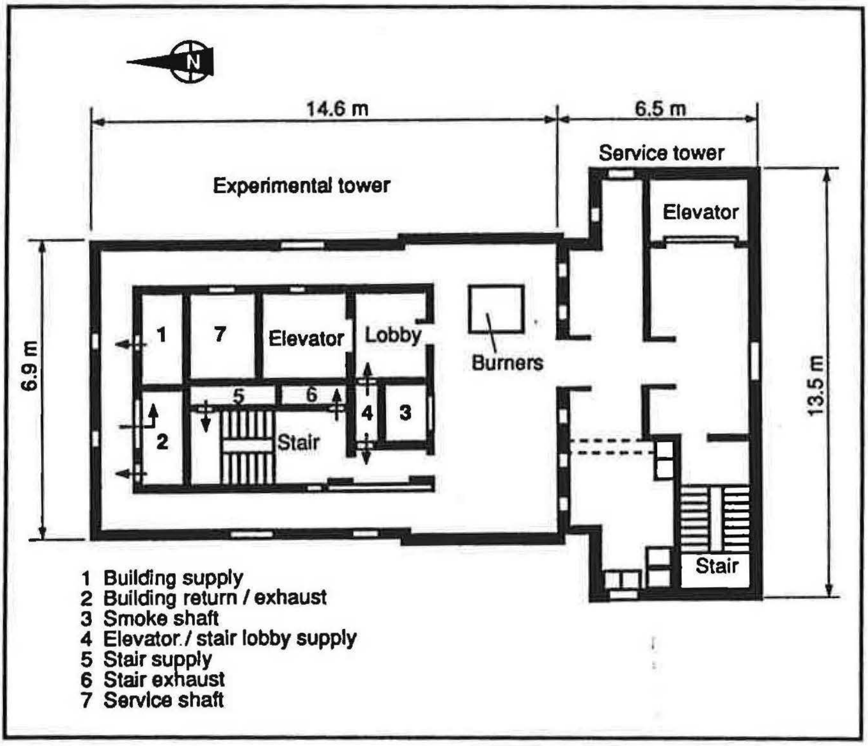

Figure 1. Experimental fire tower.

rates up to 2000 cfm (940 L/s) were measured with a metal orifice plate inserted in the duct upstream of the airflow measuring station. All tests were conducted with wind speed of less than 12 mph (20 kmh).

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

Measurements were made at fire temperatures of 150°F (65°C), 300°F (147°C), 450°F (232°C), 600°F (315°C), 750°F (400°C), 900°F (484°C), 1050°F (565°C), and 1200°F (650°C). The last three temperatures were obtained with strip propane gas burners (2.5 MW) fixed in the burn area of the second floor. Lower fire temperatures were obtained with four ganged small gas burners (total of 1.0 MW) set on top of the strip gas burners as shown in Figure 2. The test fire temperature was measured with a thermocouple directly above the burners and one foot

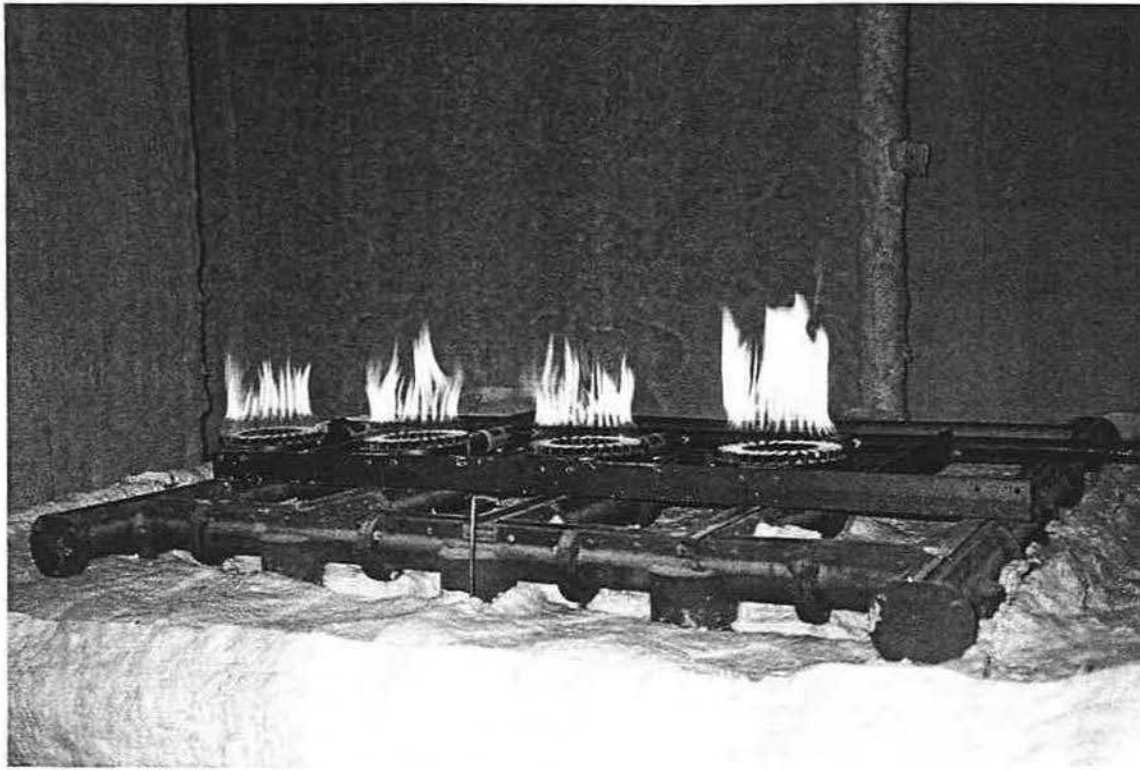

Figure 2. Two sets of test gas burners.

(0.305 m) below the ceiling, and was controlled at the test temperatures by adjusting the propane gas flow rate. The locations of other ceiling thermocouples and the three thermocouple trees in the burn area are shown in Figure 3.

Initially, tests were conducted with the above fire temperatures to determine the pressure differences across the stairshaft wall caused by fire. This was followed by tests with the stairshafts pressurized and with the stair door on the fire floor fully open. The reference test condition was outside wall vents closed, no mechanical venting of the fire floor, stair door open only on the second floor at 90°, and multiple air injection of the supply air for stairshaft pressurization. The air velocities at the stair door opening required to prevent smoke backflow were determined for the following test conditions:

1. Area of outside wall vents opening on the second floor—**0**, 10 ft^2 (0.929 m^2), 20 ft^2 (1.858 m^2), and 30 ft^2 (2.787 m^2);
2. Mechanical venting of the fire floor—**none**, venting with exhaust rate of 9800 cfm (4.62 m^3/s) to create a pressure difference across the closed stair door of 0.10 inch of water (25 Pa);

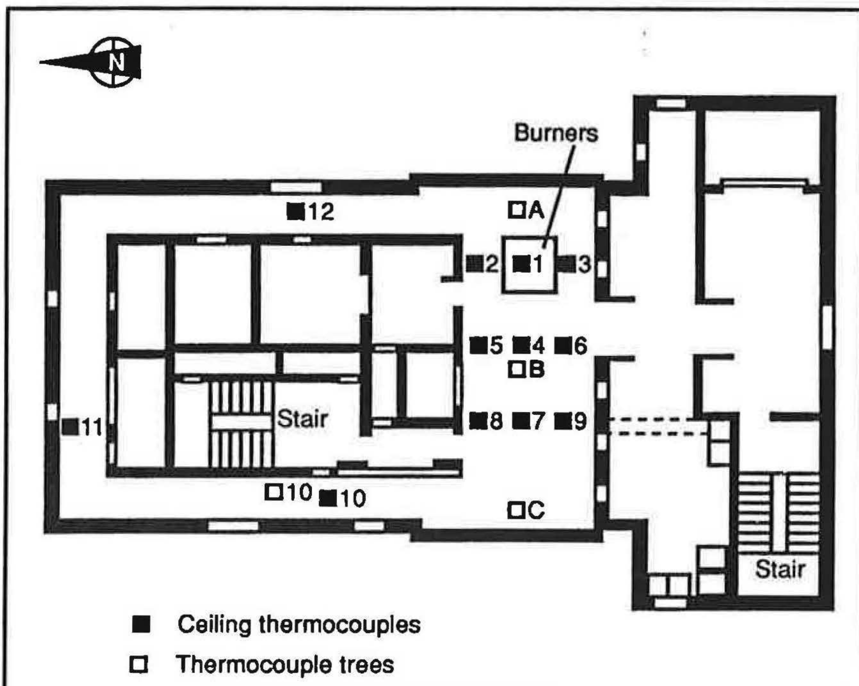

Figure 3. Location of thermocouples.

3. Number of open stair doors—**one (second floor)**, two (first and second floors), and three (first, second and third floors);
4. Angle of opening of the stair door on the second floor—**90°**, 60°, and 30°; and
5. Method of air injection for stair pressurization—**multiple injection (floors 1, 3, 5, 7 and 10)** and bottom injection (floor 1).

Note: reference case highlighted in bold type.

Both fire and non-fire tests were conducted for each of the above test conditions. During the fire tests, the supply air rate to the stairshaft was adjusted until no smoke backflow was observed as determined by running a smoke pencil along the top of the door opening. For each test, the supply air rate to the stairshaft corresponding to the point of no backflow was noted. During the following non-fire test with the stairshaft pressurized with the same supply air rate noted during the fire test, a 21-point hot wire anemometer traverse was conducted to determine the average air velocity at the stair door opening. During the tests, pressure differences across the outside walls and vertical shafts and air temperatures for all floors were recorded with the data acquisition system.

RESULTS AND DISCUSSION

Pressure Differences Across the Walls of the Test Stairshaft Caused by Fire

Fire tests were conducted with the supply air fan for the stairshaft shut down (no pressurization), and with all doors of the stairshaft closed and no venting of the fire floor. The pressure differences across the walls of the stairshaft (stairshaft pressure—burn area pressure) caused by the fire are shown in Figure 4 at ten feet (3.048 m), seven feet (2.13 m), and 1.3 feet (0.40 m) above floor level. From these pressure measurements, the neutral pressure level was found to be at 5.50 feet (1.68 m) above floor level. This is the level above which combustion gases of the fire floor flowed into the stairshaft, and below which air from the stairshaft flowed into the fire floor. The location of the neutral pressure level not only depends on the size and distribution of the leakage openings in the stairshaft walls, but also on all other leakage openings in the fire floor enclosure.

Using 5.50 feet (1.68 m) above floor level for the neutral pressure level, pressure differences across the stairshaft walls were calculated using the following buoyancy equation (Equation 1):

$$P_s - P_f = gh\rho_i (T_f - T_i)/T_i$$

where:

P_s — P_f = pressure difference across the shaft wall
g = gravitational constant
h = distance from the neutral pressure level
ρ = gas density
T = temperature

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

Equation 1 assumes uniform space air temperatures inside the stairshaft and in the fire floor. The temperatures in the fire floor, however, varied greatly both horizontally and vertically as indicated by the thermocouple readings given

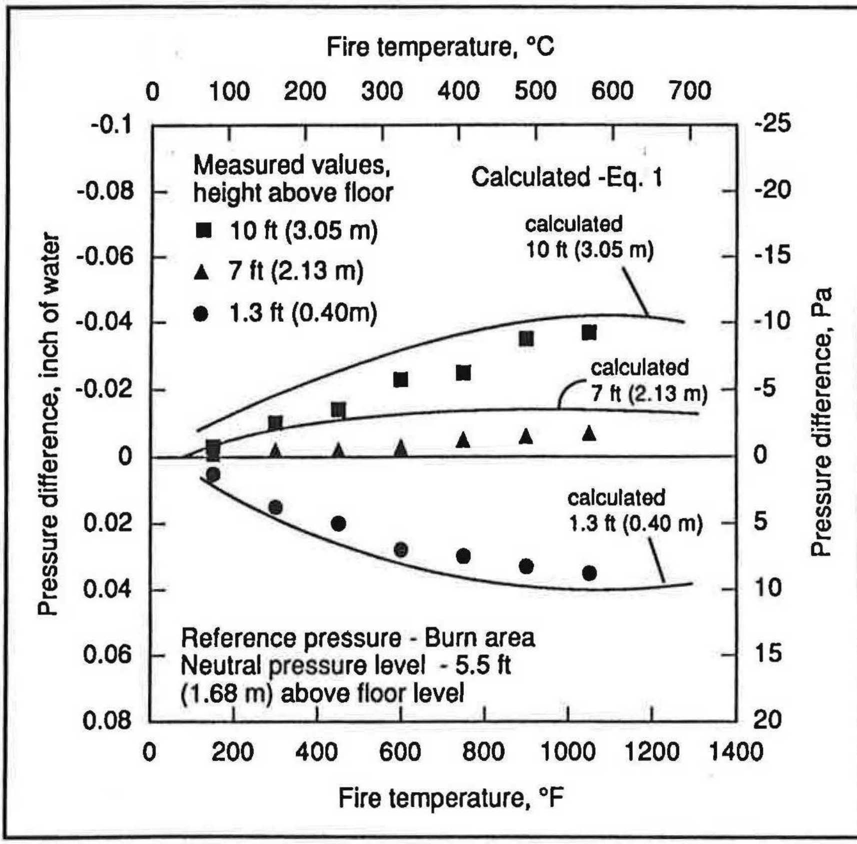

Figure 4. Pressure differences across stairshaft wall caused by fire.

in Table 1. As an approximation, the control temperatures near the ceiling above the gas burners were used in Equation 1 to calculate the pressure differences across the stairshaft walls at the three levels. As expected, the calculated values that are also shown in Figure 4 overestimated the pressure differences across the walls of the stairshaft. Based on Figure 4, the effective uniform fire temperatures in terms of Equation 1 are roughly about 75 percent of the control fire temperatures.

Table 1. Temperature Distribution on the Fire Floor for Control Fire Temperature of 1200°F (650°C)*

Test Condition
Outside wall vents closed
Multiple air injection to prevent smoke backflow
Stair door on 2nd floor open

Ceiling Temperatures

Location	Temperature °F (°C)	Location	Temperature °F (°C)
1	1170 (632)	7	921 (494)
2	900 (483)	8	—
3	1074 (579)	9	972 (522)
4	993 (534)	10	853 (456)
5	—	11	430 (221)
6	1065 (574)	12	945 (507)

Thermocouple Trees in the Burn Area

Height above Floor ft (m)	Temperatures °F (°C) A	B	C	D
10 (3.05)				818 (437)
8 (2.44)	1022 (550)	918 (492)	855 (474)	
7 (2.13)				701 (372)
6 (1.83)	993 (534)	880 (471)	855 (457)	
4 (1.22)	889 (476)	748 (398)	558 (292)	
3.5 (1.07)				430 (221)
2 (0.61)	511 (266)	505 (263)	323 (162)	
1.3 (0.40)				368 (187)

*See Figure 2 for locations of thermocouples.

Venting the Fire Floor with Exterior Wall Vents

The critical air velocities plotted against the fire temperatures for exterior wall vent areas of zero, ten, twenty, and thirty ft^2 (0. 0.93, 1.86, and 2.79 m^2) are shown in Figure 5. This graph shows that the air velocities required to prevent smoke backflow increased with fire temperature and decreased with size of the exterior wall vents. At 150°F (65°C) with the exterior wall vents closed, the critical air velocity was 124 ft/min (0.63 m/s). At the same temperature with the exterior wall vent open at 30 ft^2 (2.79 m^2), it was 91 ft/min (0.46 m/s). At 1200 °F (650°C) the critical air velocities were 460 ft/min (2.34 m/s) and 307 ft/min (1.56 m^2), respectively. The critical air velocity with an exterior wall vent opening of 30 ft^2 (2.79 m^2) was about 70 percent of that with the exterior wall vents closed. Further

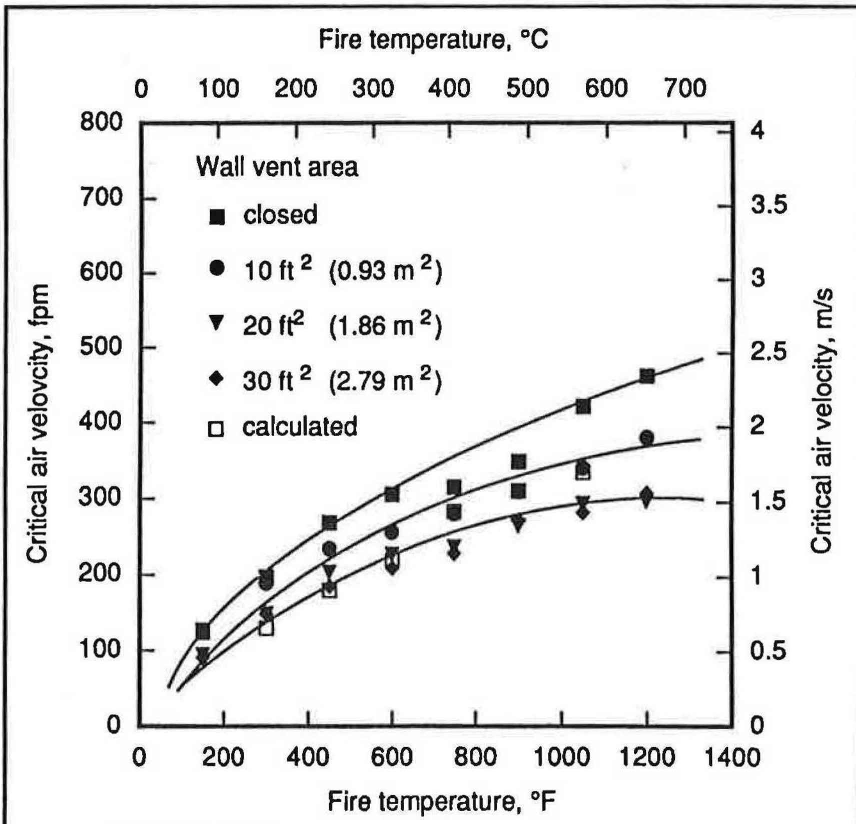

Figure 5. Effect of outside wall vent area on critical air velocity.

increase in vent area is unlikely to result in any significant reduction in the critical air velocities.

With the outside wall vents closed, smoke backflow cannot be prevented if the enclosure of the fire floor is airtight. The pressures of the fire floor would then increase to equalize with those of the stairshaft, resulting in an exchange of air and smoke at the stair door opening caused by the buoyancy force. The extent of buildup of pressures in the fire floor would depend on the leakage area of the fire floor enclosure, and the buildup would be indicated by the pressure differences across outside walls and walls of the vertical shafts, such as an elevator shaft. The pressure differences across the elevator shaft wall measured during the non-fire tests are shown in Figure 6. The buildup of pressures was greatest with the outside wall vents closed, but was reduced significantly with vent area of 10 ft^2 (0.93 m^2), and was negligible for vent sizes of 20 and 30 ft^2 (1.86 and 2.79 m^2). Airflow through the stair door to prevent smoke backflow can cause buildup of pressures in the fire floor, which can result in increased rate of smoke flow into elevator and service shafts. On the other hand, this airflow can assist firefighters in entering the fire floor by increasing visibility and reducing air temperature around the stair door.

Using the measured values of pressure differences across the stairshaft wall at the seven-feet (2.13 m) level of Figure 4, the corresponding air (smoke) velocities at the top of the stair door were calculated as follows:

$$P_v = \rho \frac{V^2}{2}$$

or, for air density at standard temperature and pressure, Equation 2:

$$V = C\,(P_v)^{1/2}$$

where: P_v = velocity pressure, inch of water (Pa)
ρ = air density, lb/ft^3 (kg/m^3)
V = air velocity, ft/min (m/s)
C = 4000 (1.29), ft/min / (inch of water)$^{1/2}$ (m/s / $Pa^{1/2}$).

The air velocities thus calculated from Equation 2 are also plotted in Figure 5. This curve lies just above the curve for the outside wall vent opening of 30 ft^2 (2.79 m^2). With no pressure buildup on the fire floor, critical air velocities can be estimated using Equations 1 and 2.

It should be noted that the critical air velocities correspond to no smoke backflow at the top of the door opening. However, smoke can flow into the stairshaft through any crack openings in the stairshaft walls above the door opening.

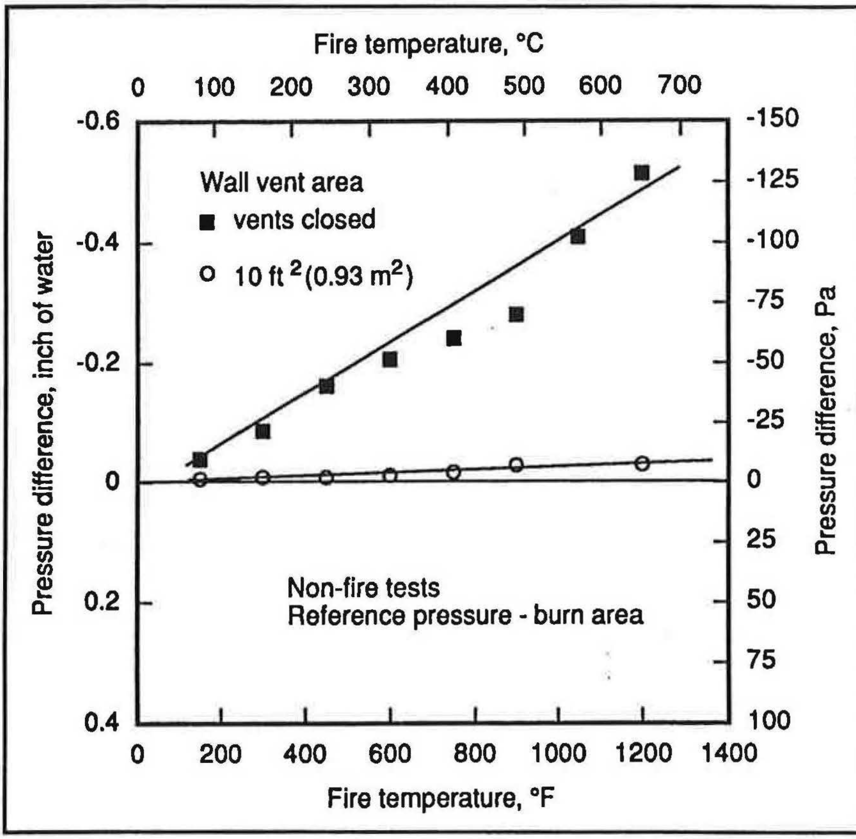

Figure 6. Pressure differences across elevator shaft walls with stairshaft pressurized to prevent smoke backflow.

Mechanical Venting of the Fire Floor

With the exterior wall vents closed, the fire floor was mechanically exhausted at a rate of 5.5 ach to produce a pressure difference across the stair door of 0.10 inch of water (25 Pa). Then, under fire conditions, the stairshaft was pressurized with the stair door open on the second floor to conduct the smoke backflow tests. Critical air velocities thus obtained (shown in Figure 7) were less than those with the exterior wall vents closed, and were about the same as those with the exterior wall vents open at 30 ft^2 (2.79 m^2), as shown in Figure 5. The corresponding required air supply rates to the stairshaft are shown in Figure 8. The supply air rates were considerably less with the fire floor mechanically exhausted than for the case with exterior wall vents open at 30 ft^2 (2.79 m^2). Also, at a fire

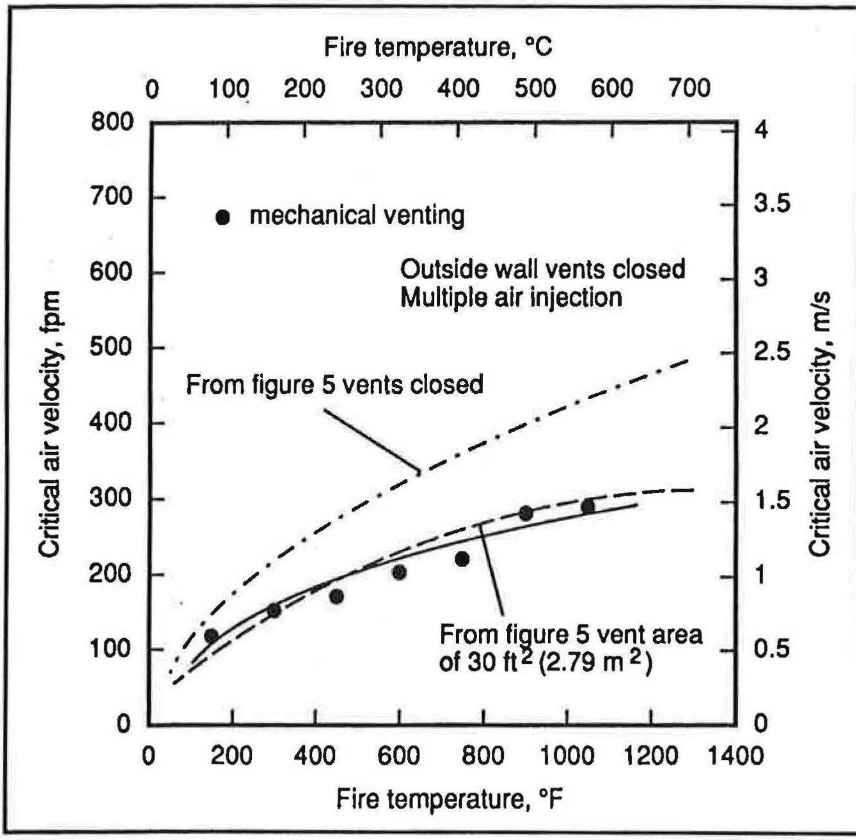

Figure 7. Effect of mechanical venting on critical air velocity.

temperature of 150°F (65°C), mechanical venting alone induced sufficient airflow at the stair door opening to prevent smoke backflow.

Angle of Stair Door Opening

The results of the tests with the stair door on the second floor open at an angle of 30°, 60°, and 90° are shown in Figure 9. Because a velocity traverse could not be conducted with the stair door partially open, the airflow through the stair door opening was determined by subtracting the air leakage flow through the entire stairshaft walls from the measured supply air to the stairshaft. The air leakage flow was calculated knowing the leakage areas of the stairshaft walls and the measured pressure differences across their walls on all floors. The airflow rates at the stair door opening thus obtained were divided by the area of the stair door at a fully

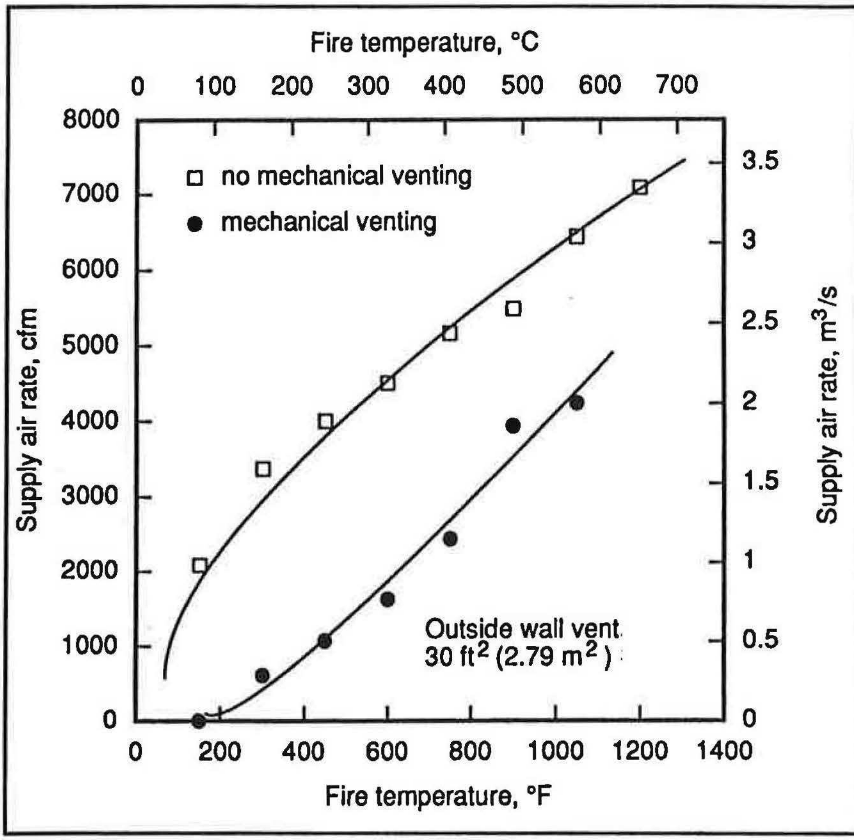

Figure 8. Comparison of required air flow rates to prevent smoke backflow with and without mechanical venting.

open position to obtain comparative critical air velocities in terms of airflow rates. Figure 9 indicates that with the stair door open at 60°, they were about 85 percent of those with the stair door fully open, and about 50 percent with the stair door open at 30°. Therefore, keeping the stair door open to a practical minimum during a fire can minimize the possibility of smoke contamination of the stairshaft.

Number of Open Stair Doors

The effect of opening several stair doors on the critical air velocities is shown in Figure 10. The top curve represents the critical air velocities with the outside wall vents closed, and with only the stair door on the second floor (fire) open. The critical air velocities with the stair doors open on floors one and two, and with the

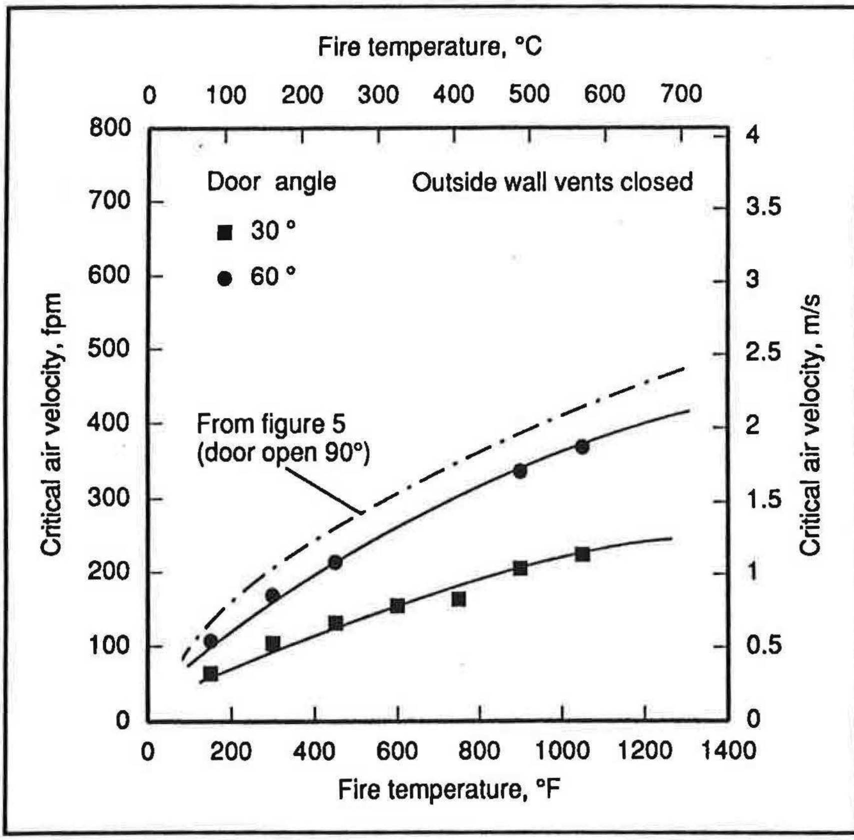

Figure 9. Effect of open door angle on critical air velocity.

stair doors open on floors one, two, and three, were about the same and about 75 percent of that with only the stair door on floor two open. This was surprising, as critical air velocities greater than those with only the stair doors on floor two open were expected; these results could not be explained.

Method of Air Injection

Figure 11 compares the critical air velocities obtained with the stairshaft pressurized with multiple air injection on floors one, three, five, seven, and ten, and bottom injection only on floor one. The critical air velocities with the exterior wall vents closed indicated practically no differences between the two methods of air injection.

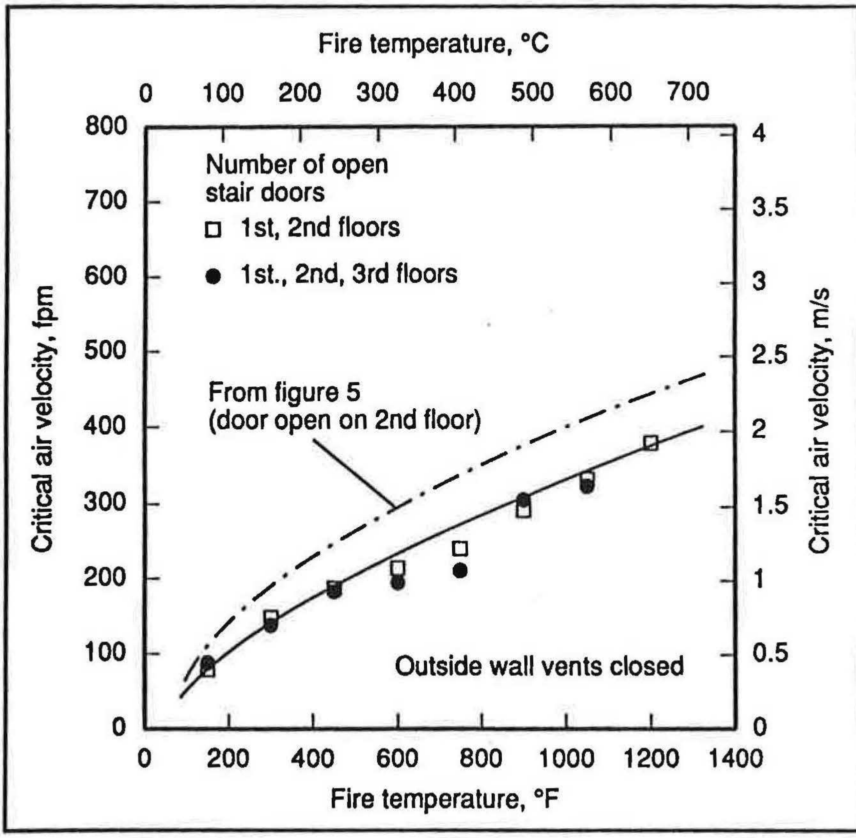

Figure 10. Effect of number of open stair doors on critical air velocity.

SUMMARY

The critical air velocities for a given building can be calculated using equations for buoyancy and velocity pressure (Equations 1 and 2) for cases with no pressure build-up in the fire floor caused by air flow through the stair door into the fire floor.

The initial tests in the experimental fire tower were conducted to determine critical air velocities with fire temperatures ranging from 150° (65°C) to 1200°F (650°C). The stairshaft was pressurized with multiple injection of supply air and stair door was open at 90° on the fire floor with no venting on this floor (reference test condition). For the range of test fire temperatures, the critical air velocities increased from 124 ft/min (0.63 m/s) to 460 ft/min (2.34 m/s). The critical air velocities for other test conditions were compared with these values.

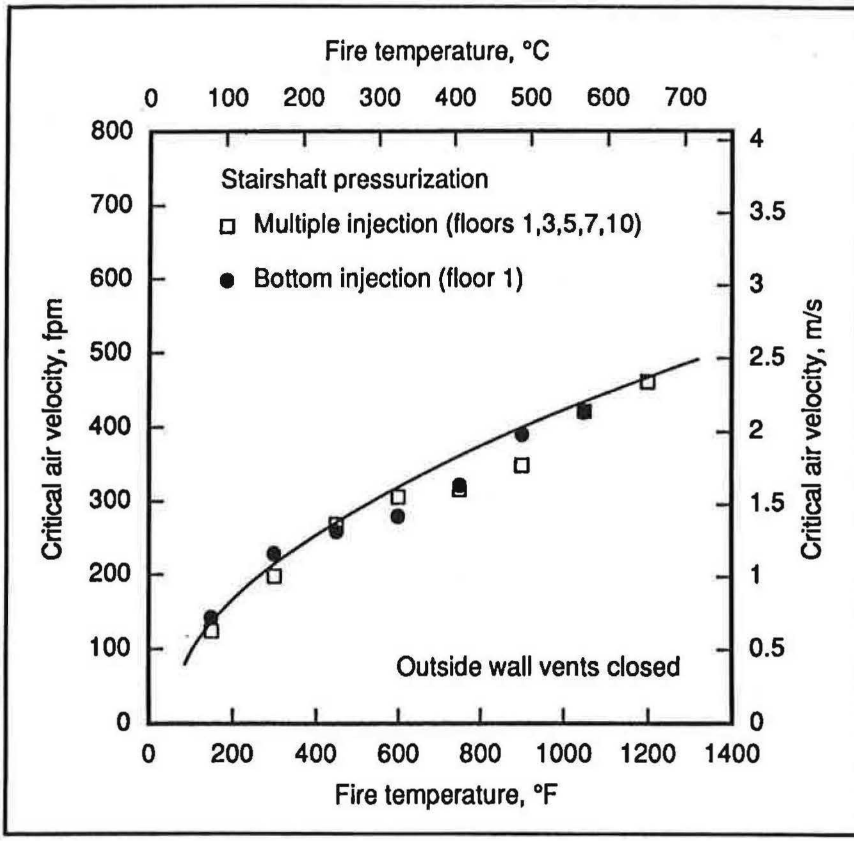

Figure 11. Effect of method of air injection.

The critical air velocities decreased to a minimum of 70 percent of those with the exterior wall vents closed when the size of the exterior wall vents was increased to 30 ft^2 (2.79 m^2). They decreased with mechanical venting at 5.5 ach to the above minimum values. Critical air velocities also decreased to 85 percent of those with only the stair door open on the second floor when the stair door on the first floor was also opened; and were about the same when, in addition, the stair door on the third floor was opened. They were about the same for multiple injection and bottom injection of supply air for stairshaft pressurization. The supply air rates required to prevent smoke backflow decreased with angle of stair door opening at 60° to 85 percent of those with door angle of 90°, and decreased to 50 percent with stair door angle of 30°.

The values of critical air velocities for various cases given in this article can serve as a guide for estimating the supply air rates required for open door conditions in designing stair pressurization systems. The critical air velocities to use for that purpose are likely to be those obtained with the reference test condition at the design fire temperatures.

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