#6108

FIRE PROTECTION & SMOKE CONTROL

DESIGN OF A STAIRSHAFT PRESSURIZATION SYSTEM FOR TALL BUILDINGS

Pressurization by injecting outdoor air into a stairshaft is one means of maintaining tenable conditions in it during a fire emergency. Studies were made on various factors that govern performance of stairshaft-pressurization systems. Proposed here is a design for one such system. The performance of this system under various fire conditions was investigated using a computer model of the building.

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THE pressurization of stairshafts as a method of providing escape routes in the event of a fire has received much attention in recent years because of its apparent ease of application to both new and existing buildings. It involves raising the pressure in the stairshaft by injecting outdoor air so that the direction of flow is from the shaft to its surroundings, thus preventing smoke from entering the stairshaft.

Recent tests conducted under non fire[1], simulated fire[2] and actual fire[3,4] conditions demonstrated that such systems can be effective in keeping the stairshafts free of smoke under certain conditions. They also indicated that substantial loss of pressurization and, hence, the possibility of smoke contamination, can occur when several stair doors are open simultaneously, and that excessive pressure differences can develop across some stair doors which would make them difficult to open.

Information necessary for the design of stairshaft pressurization systems is as yet incomplete. Although there are requirements adopted by a few well known building codes[5,6,7], which are summarized and listed in Table I, it is difficult for a designer, at present, to design a system that will meet such requirements. The results of fire tests can offer the designers some useful data in this regard but they are far from complete. The purpose of this paper is, therefore, to propose one practical approach to the design of such a system.

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DESIGN CONSIDERATION

• Required Pressurization

The object of pressurizing a stairshaft is to raise its pressure to a level higher than that in the surrounding areas, particularly the fire floor. Measurements of pressures developed in test fires[3,8] indicate that a fire can cause pressures in the fire area that are higher than those in the adjacent stairshafts by about 0.05 in. of water. This value can be exceeded momentarily up to a value of 0.15 in. of water during the course of a fire.

Stack action during cold weather can also cause adverse pressure differences across stair doors located below the neutral plane of the stairshaft. The worst situation is when the fire occurs near ground level and the windows on the fire floor are broken. If this occurs, the pressure differences across stair doors on the fire floor are approximately one half of the total pressure difference caused by stack action, which depends on the building height and the difference in temperatures between inside and outside. For example, with an outside temperature of 0F and an inside temperature of 75F and assuming that the neutral pressure plane is located mid-height of the building, the maximum adverse pressure difference across a shaft wall is 0.3 in. of water for a 20-story building and 0.7 in. of water for a 50-story building. These values are much greater than those caused by a fire confined to a single story. The adverse pressure differences caused by stack action during cold weather can be overcome, however, with bottom venting of the stair shaft[9], *i.e.*, by opening the stair door at ground level to the exterior or to a lobby with an opening to the exterior.

From the foregoing consideration a minimum pressurization of 0.10 in. of water seems appropriate to overcome pressures caused by fire alone. This assumes that all stair doors are closed

except for the one on the exit level so that bottom venting can counteract pressure differences across stair doors caused by stack action during cold weather.

• Required Flow Rate

The flow rate required to achieve a pressurization of 0.10 in. of water for a shaft with little resistance to flow with all stair doors closed except for the one at the exit level is given by the following equation[7]:

$$Q = 15{,}000 + 200N \qquad (1)$$

where Q = air flow rate, cfm
N = number of storys

The value of 15,000 is the calculated flow rate in cfm through an open stair door approximately 20 sq ft at the exit level; the value of 200 is the calculated flow rate in cfm per floor through the shaft walls, assuming a typical leakage area per floor equivalent to an orifice area of 0.20 sq ft for the stair door and 0.05 sq ft for the shaft walls[10]. The flow rate has to be modified if the stairshaft has leakage openings other than as assumed.

This approach to specifying the rate of supply air is the one adopted by the Canadian Standards. As seen in Table I, the requirements for the supply air rate in either the New York or the Australian Standards are not given but may be calculated to satisfy other requirements such as pressure differences across stair doors and flow velocity across open stair doors.

Table I — Code Requirements For A Stairshaft Pressurization System

	Australian Standard	New York City Standard	Canadian Standard	Remarks
Air Flow Rate (cfm)	Not specified	Not specified	15000 . 200 per story¶	¶ Based on open exit stair door with all others closed.
Minimum average air velocity through any two open stair doors of two successive floors (fpm)	200*	Not specified	Not specified	* In addition, main exit stair door is also open.
Maximum air velocity through an open stair door (fpm)	Not specified	2000	Not specified	
Maximum door opening force (lb)	Not specified	25†	Not specified	† Permits mechanical assistance as required
Maximum pressure difference across a stair door (in. of w.g.)	0.20	Not specified	0.40	
Minimum pressure difference across a stair door with three stair doors open. (in. of w.g.)	Not specified	0.05(fire floor) 0.02(others)	Not specified	Three doors include the stair door on the design fire floor, the door below or above the fire floor and the one at the point of air injection.

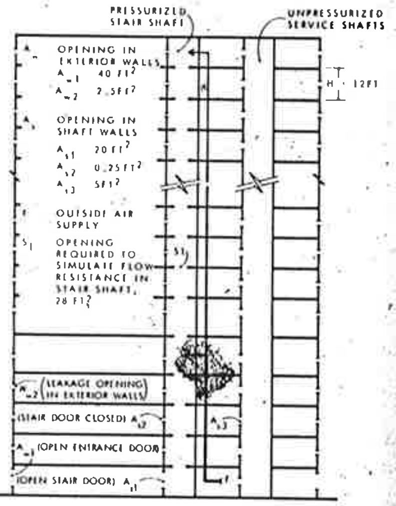


Fig. 1. Computer model building

• Method of Air Injection

Migration of smoke into the stairshaft due to loss of shaft pressurization can be expected occasionally because of the opening and closing of a number of stair doors during the course of a fire. The air supplied to the shaft can serve the secondary function of diluting smoke when this happens. This may not happen if the air is supplied at a single point as a substantial portion of the supply air is lost when a few doors are open near the point of injection. Consequently, there may be little air for pressurization or dilution near the fire floor if it is located far from the point of injection. Tests have indicated that with a single point of air injection, pressure differences across some stair doors can exceed 0.40 in. of water, which will interfere with their operation[1,2,3,4]. The injection of air at each floor or at least at every fifth floor should assure uniformity of flow throughout the shaft even with several stair doors open.

COMPUTER MODEL STUDIES

The foregoing discussion indicated

that the following steps should be taken in designing a stairshaft-pressurization system.

1. Determine the supply air flow rate from Eq. (1).

2. Assume injection points at least on every fifth floor.

3. Establish that the maximum pressure difference across stair doors is no more than 0.40 in. of water.

The first two requirements are straightforward. A mathematical model of a building, shown in Fig. 1, was devised to investigate whether satisfying the first two requirements would ensure that the third would also be satisfied. The model contains two shafts, one representing the pressurized stairshaft and the other the various unpressurized shafts such as elevators and service shafts.

The leakage openings in the external and internal separations of the model are lumped and replaced by equivalent orifice areas. Their sizes, based on field measurements[10], are given in Fig. 1. The flow resistance in the stairshaft is simulated by a series of orifice areas, one for each story, located in a fictitious separation between adjacent floors in the shaft. The size of the orifice area is such that the pressure drop across it is equivalent to that caused by the shaft for one floor height. This fictitious orifice area is about 28 sq ft for a stairshaft with a cross-sectional area of 100 sq ft, based on measurements made on several buildings.

The mass flow of air through the various openings can be represented by

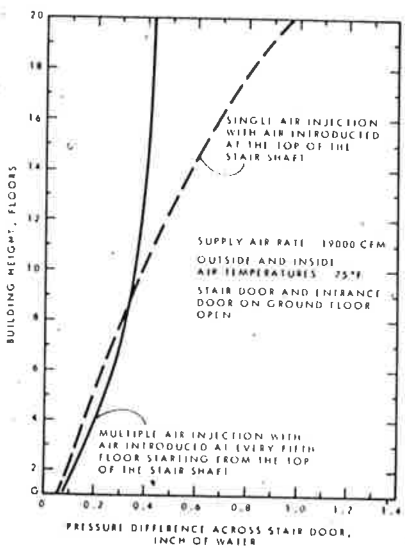


Fig. 2. Pressure differences across stair doors with single and multiple air onjections

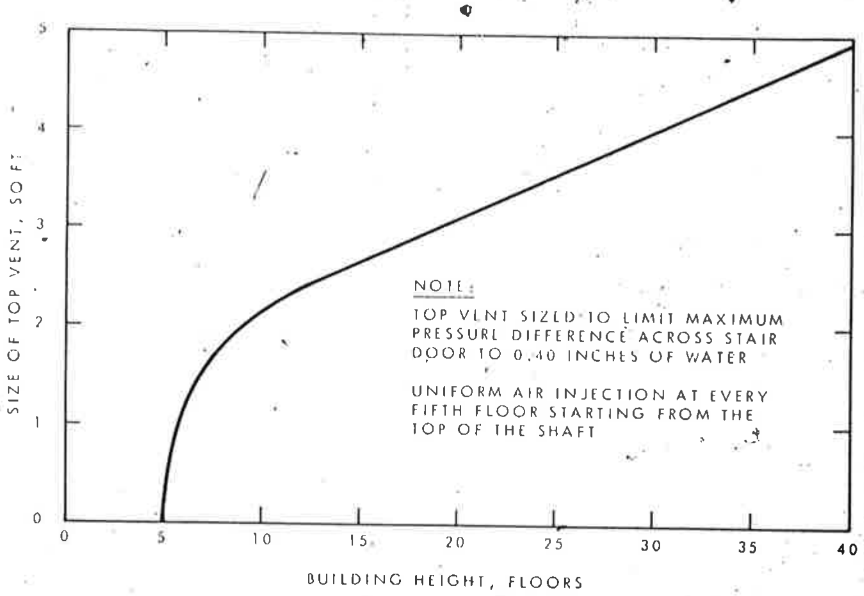


Fig. 3. Size of top vent vs building height

$$W = CA\rho^n \Delta P^n \quad (2)$$

where W = mass flow
C = proportionately constant
A = orifice area
ρ = air density
ΔP = pressure difference across opening
n = flow exponent (n = ½ used)

For a given outside condition of wind and temperature all outside pressures can be specified. By setting up mass flow balance equations for each compartment all inside pressures can be computed using Eq. (2). The details of the computer model and the computer program are given in Ref. 11.

• Control of Pressure Differences Across Stair Doors

Initial calculations were made with air injection at the top of the stairshaft of a 20-story model building and also at every fifth floor starting from the top. The supply air rate based on Eq. (1) was 19,000 cfm. Inside and outside temperatures were assumed to be equal. The pressure differences across the stair doors for both cases are given in Fig. 2. With air injection only at the top the pressure differences across the stair doors at upper levels exceeded the limiting value of 0.40 in. of water. These differences were greatly reduced with multiple injections. Investigation of multiple injections under winter conditions resulted in pressure differences somewhat greater than those under summer conditions. The case of air injection only at the bottom was not considered as it would not provide sufficient air for dilution because of the substantial quantity of air that would be lost through the open exit door on the ground level.

Although excessive pressure differences across stair doors are reduced with multiple injections as shown on Fig. 2, further reductions are required to bring them to an acceptable level. This can be achieved by providing a relief vent at the top of the stairshaft together with multiple injections. The vent sizes required to reduce maximum pressure differences to just below 0.40 in. of water were calculated for stairshafts of various heights for both winter and summer conditions. Those calculated under winter conditions (outside temperature 0F) are plotted in Fig. 3 as they were found to be greater than those obtained under summer conditions. It was assumed that the outside air supplied to the stairshaft was heated to inside ambient temperature. The amount of air vented to the exterior at the top depends on the pressure difference across the top vent. In the event of loss of shaft pressurization caused by opening stair doors, the supply air for dilution is increased as the rate of air flow through the top vent is decreased.

The calculation of top vent size was based on a stairshaft with a gross cross-sectional area of 100 sq ft, which is the usual size in most buildings. For a larger stairshaft, the required vent size would be smaller as the flow velocity and, hence, the pressure loss in the stairshaft would be less.

• Effect of Outside Air Temperature

Fig. 4, giving pressure differences across the stair doors for summer (Curve 1 — outside temperature 75F) and

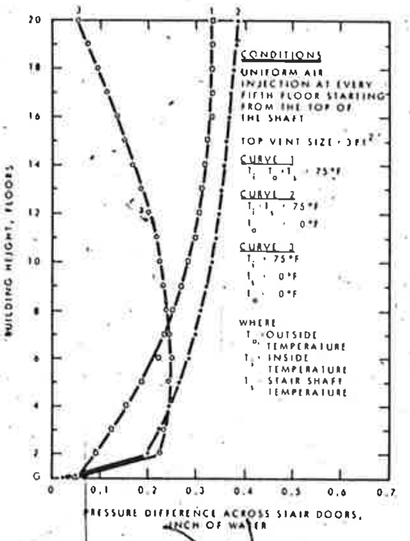


Fig. 4. Dependence of pressure difference across stair doors on outdoor and shaft temperatures

winter (Curve 2 — outside temperature 0F), illustrates the effect of outside air temperature on the performance of a stairshaft-pressurization system. In both cases the top vent size was 3 sq ft as selected from Fig. 3 and the supply air temperature was 75F. It can be seen that the amount of pressurization is generally greater under winter than under summer conditions. This is due to stack action during winter causing a reduction in the outflow of supply air through the opening of the stair door on the ground floor.

If the outside supply air for pressurization is not heated in winter, the shaft air temperature can be expected to be lower than the inside ambient temperature. Curve 3 of Figure 4 shows the effect of 0F shaft temperature. Comparison of Curves 3 and 2 shows that lower shaft air temperature results in a reduction in the pressure differences across stair doors. It can be seen that the amount of reduction increases from the 2nd floor upward. The minimum pressure difference, which occurs at the top floor, is about 0.05 in. of water. It is probable that the air temperature of the shaft would be higher than the outside temperature due to heat transfer from the surroundings[1] which would result in shaft pressures that are higher than those given by Curve 3. This suggests that it is not necessary to heat the air supplied to the stairshaft for effective pressurization although it is probably desirable to provide some heating for the comfort of the people in the stairshaft.

- **Effect of Fire Temperature**

Computer simulations indicate that stairshaft pressurization will prevent the flow of smoke into the stairshaft for the 20-story model building with a temperature of 1000F at the fire floor and all stair doors closed except for the one at the exit level. The case of a fire on the second floor was investigated for both summer and winter conditions. If the stair door on the fire floor is open (20-sq ft opening), the results indicate that there would be a 3500-cfm flow from the stairshaft into the fire floor through the lower portion of the opening and a 680-cfm flow of smoke from the fire floor into the stairshaft through the upper portion of the opening. When there is a substantial flow of pressurization air into the fire floor through an open stair door, as in this example, the pressures in the fire floor are increased resulting in a lower pressure difference across the shaft wall. If in addition the fire floor is vented to the exterior (*e.g.*, by window breakage caused by fire), the flow of smoke into the stairshaft is reduced from 680 to 330 cfm. It would be unlikely, however, that a stair door at the fire floor would remain open for fire fighting if the temperature close to it was 1000F. An assumption of a lower temperature of 200F indicated that the flow of smoke into the stairshaft is 310 cfm for an unvented fire floor and 0 cfm for a vented fire floor. The amount that the stair door is opened to the fire floor should be kept to a minimum, firstly to minimize the quantity of smoke and heat escaping into the stairshaft under adverse conditions and secondly to minimize the flow of pressurization air into the fire floor which could cause flow of smoke into unpressurized vertical shafts and to other floors.

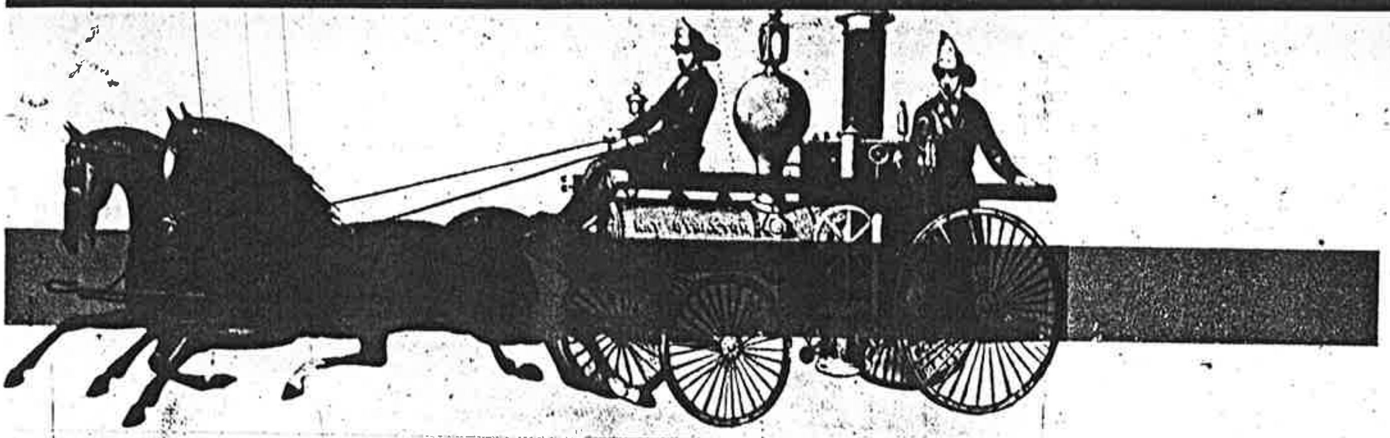
- **Effect of Open Stair Doors**

It can be expected that a number of stair doors will be open during evacuation; the worst situation is when all stair doors are open at the same time under summer conditions. To simulate this, it was assumed that the opening of each stair door was 5 sq ft, allowing for blockage by persons entering the stair shaft.

The test run with a fire temperature of 1000F on the 2nd floor, with its stair door closed but with all other stair doors open, resulted in a 30-cfm flow of smoke into the stairshaft. This represents a smoke concentration in the stairshaft at the 2nd floor of about 2.0 per cent of that of the fire floor. If the fire floor is vented the smoke concentration is less than 1.0 per cent. These conditions are likely to be temporary and localized to the fire floor area and, hence, it is not expected that it would hamper normal evacuation.

In the case of a fire temperature of 200F and the stair door on the fire floor open (20 sq ft), there was a smoke flow into the stairshaft of 970 cfm, which gives a much higher level of smoke concentration than for the previous case. Venting of the fire floor together with minimizing opening the stair door for fire fighting will greatly reduce the rate of smoke flow into the stairshaft.

It is apparent that some smoke contamination of the stairshaft can be expected during fire fighting and evacuation and it is necessary, therefore, to provide an adequate flow of air in the stairshaft to flush the smoke away. It is suggested that the supply air rate should not be less than 500 cfm per floor which represents an air change rate of once every 2 minutes for a 100 sq ft stairshaft. The time taken to clear the stairshaft to 1 per cent of its original level, assuming no further flow of smoke into the stairshaft, is 7 to 8 mi-



nutes. The supply air rate based on Eq. (1) provides a minimum of 500 cfm per floor for buildings of up to 40 stories. A total supply air rate in excess of that based on Eq. (1), therefore, would be required for taller buildings. Vents at other levels in addition to the one at the top would probably be required to control excessive pressure differences across stair doors.

PRESSURIZATION FAN

Multiple injections of supply air as recommended in this paper would involve a number of fans or a single fan with a vertical air distribution duct. For the latter case, it is preferable to locate the fan near the bottom rather than at the top of the shaft for the following reasons:

1) The power supply to the fan can be protected more easily;

2) Operation of the fan at start up is simplified as the supply of air is assisted by stack action during cold weather;

3) In the event of fan failure during winter, stack action will induce outside air into the stairshaft through the fan and duct system; and

4) Possibility of ingesting smoke from outside the building at the fan intake is less.

The required static pressure across the fan at the design flow rate for the two fan locations is as follows:

1) Fan at the bottom — the sum of the pressure losses in the vertical air distribution system and the maximum permissible amount of pressurization of 0.40 in. of water; and

2) Fan at the top — the sum of the pressure losses in the vertical air distribution system and 0.40 or the total pressure difference caused by stack action at the winter design temperature whichever is greater.

For the type of system considered in this paper, the exit stair door on the ground floor should be open prior to fan startup, otherwise, normal operation of stair doors may not be possible because the pressure in the stairshaft would be too great. The possibility of over pressurization of the shaft can be prevented with a relief damper in the shaft wall.

CONCLUSION

The type of stairshaft-pressurization system investigated was as follows:

- Supply air rate based on Eq. (1);
- Air injection at every fifth floor; and
- Control of excessive pressure differences with a top vent according to Fig. 3.

Computer studies indicate that this system is effective in maintaining tenable conditions in the stairshaft during evacuation with all stair doors open except the one on the fire floor. If the stair door on the fire floor is also open, heavy smoke contamination of the stairshaft may occur, depending on the size of opening. Venting of the fire floor either accidentally (window breakages) or intentionally (exterior wall vents, mechanical venting or smoke shaft) can greatly reduce the amount of smoke contamination. A low temperature fire (*e.g.*, in a sprinklered building) will reduce the possibility of stairshaft contamination.

It is possible that the operation of stair doors during evacuation and fire fighting may cause the flow of smoke into the stairshaft. There should be adequate supply air, therefore, for dilution and dispersal of smoke. Multiple injection of supply air is more effective than single injection for providing a uniform supply of air for dilution throughout the stairshaft as well as in reducing excessive pressure differences across stair doors caused by the flow resistance of the stairway.

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