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Field Checks on Building Pressurization for Smoke Control in High-Rise Buildings

Measurements made on two buildings reveal that leaky wall construction of a smoke shaft can seriously affect the performance of a smoke control system. Also revealed is that a stairshaft can be contaminated with smoke, particularly in summer when the stair door on the fire floor and the exit door of the same stairshaft are opened at the same time.

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THE 1970 edition of the National Building Code of Canada contained various recommendations for preventing smoke migration through buildings.[1] These recommendations were originally developed by using a computer model to calculate the pressure distribution and air flow between compartments under various operating conditions. Several large buildings were built during the early 70s incorporating one or another of these recommended procedures, thus it became possible to check the computer predictions against the performance of these real buildings. This paper describes the concept of the building pressurization method and gives the results of field tests on two buildings using this method. It also presents the modifications to the requirements in the National Building Code of Canada that have been made as a result of these tests.[2]

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CONCEPT

The basic concept of the building pressurization method for controlling smoke movement is to create a lower pressure on the fire floor than in adjacent spaces. This is done by raising the pressure inside the building and venting the fire floor. Thus, smoke generated on the fire floor is prevented from spreading to other parts of the building.

Fig. 1a shows air flow and pressure patterns caused by stack action during winter. Under this condition, with a fire on a lower floor, smoke can invade vertical shafts such as elevator and stairwells and rise to upper floors. If, as shown in Fig. 1b, the building was pressurized but with the vertical shaft and floor space pressures less than the outside pressures at the lower part of the building, breakage of windows on the fire floor (creating large openings in the exterior wall) could cause the pressures of that floor space to equalize with outside pressures, which would negate the benefit of the venting action of a smoke shaft or mechanical

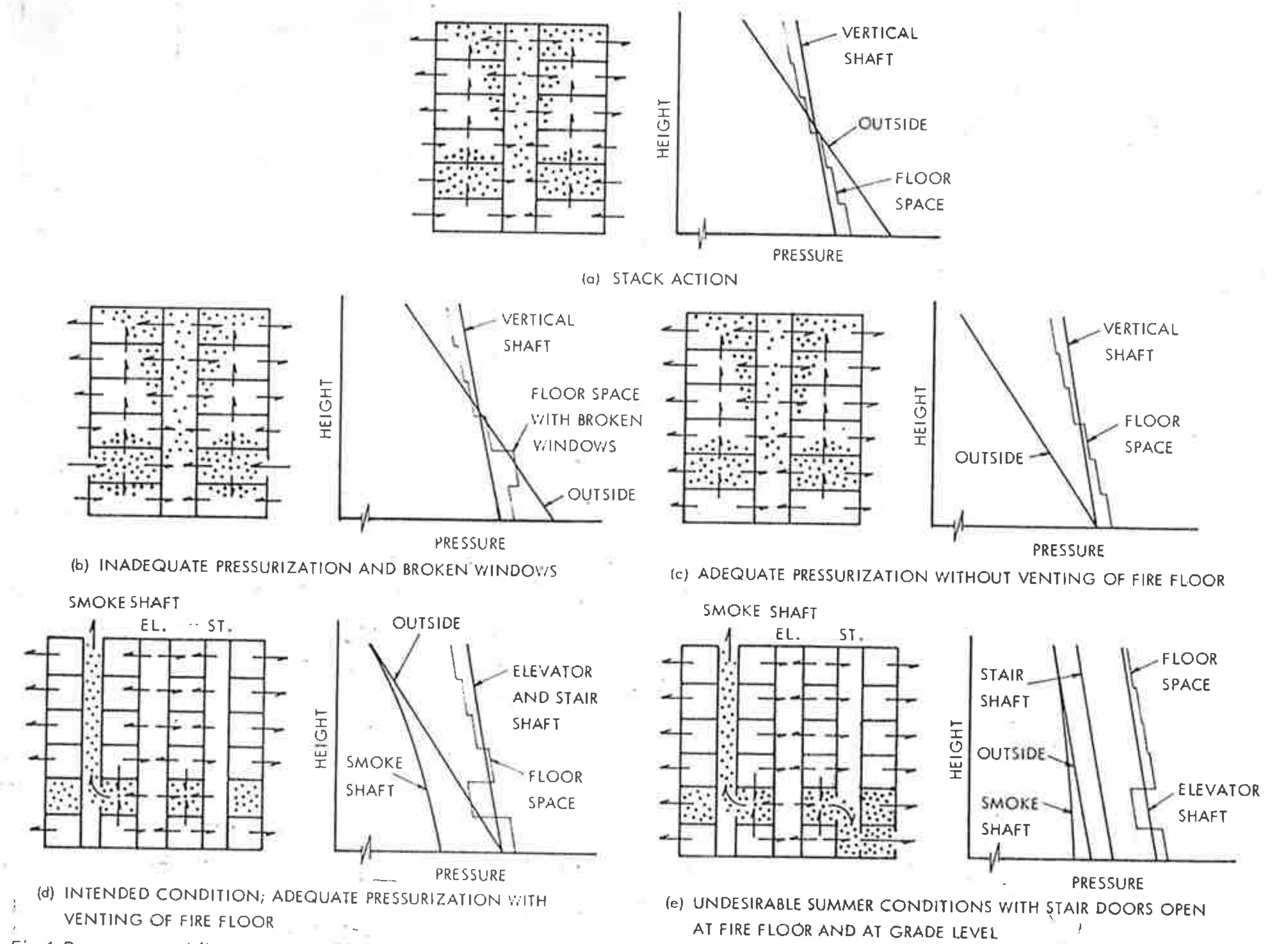

Fig.1 Pressure and flow patterns; (1a) stack action; (1b) inadequate pressurization and broken windows; (1c) adequate pressurization without venting of fire floor; (1d) intended condition; adequate pressurization with venting of fire floor; (1e) undesirable summer conditions with stair doors open at fire floor and at grade level.

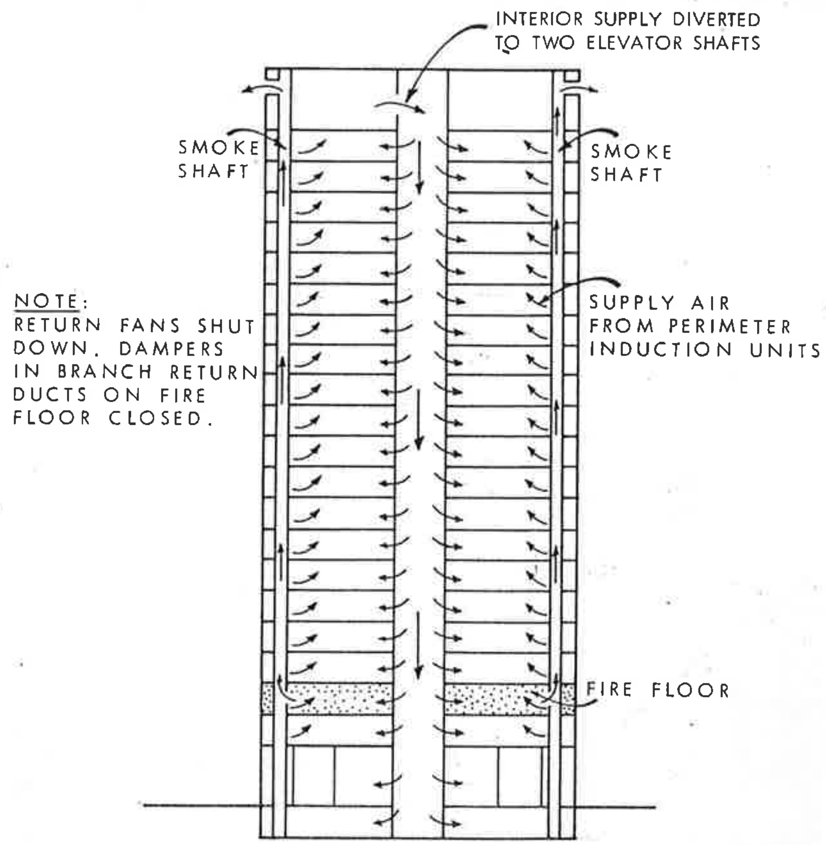

Fig. 2 Smoke control system—Building A

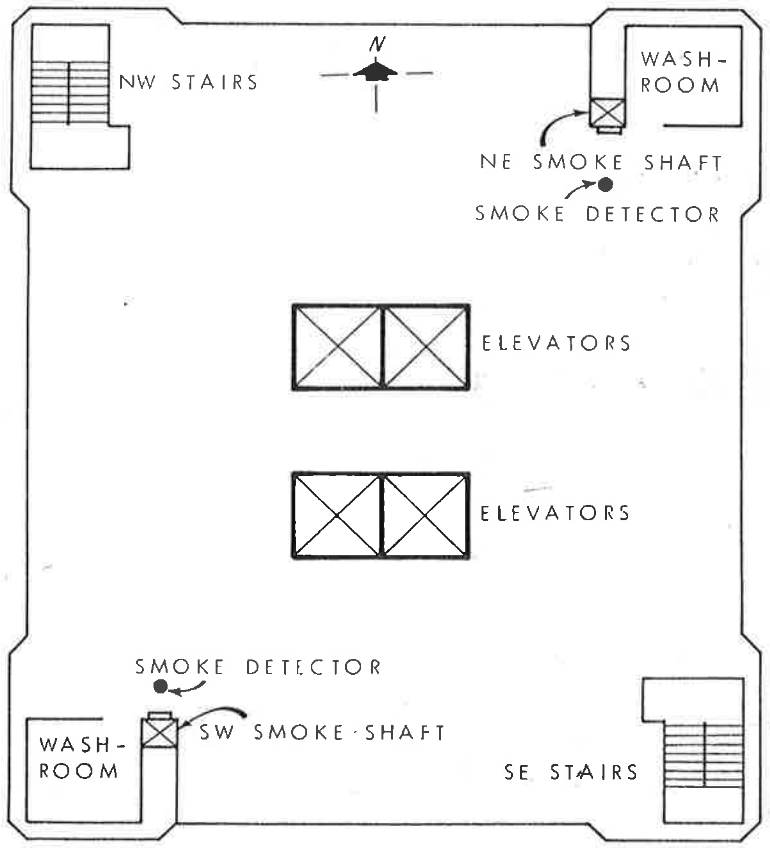

Fig. 3 Typical floor plan—Building A

exhaust.

Fig. 1c shows the building so pressurized that the vertical shaft and floor space pressures are equal to, or greater than, the outside pressures at all levels. It should be noted in this figure that with no venting of the fire floor, the air and smoke flow patterns inside the building are the same as in Fig. 1a with no pressurization. In this case breakage of windows on the fire floor will cause the pressures to decrease below those of adjacent spaces. The ideal condition is shown in Fig. 1d where the building is adequately pressurized and the smoke generated on the fire floor is expelled safely outdoors by a smoke shaft or exhaust fan. Fig. 1e shows the undesirable conditions that occur when stair doors are open both at grade level and on the fire floor.

It can be seen that considerable pressurization of the building is necessary when a large opening is created in the exterior walls of the fire floor located at a low level. If it can be assumed that such an opening is unlikely to be created, as in the case of a windowless building or perhaps in a fully sprinklered building, pressurization of the building is not required and mechanical venting of the fire floor should be sufficient.

The required rate of outside air supply for adequate pressurization—a function of outdoor temperature, building height and air tightness of the building enclosure—is given in Ref. 2. Requirements for venting the fire floor either by smoke shaft, exterior wall vents or mechanical venting are also given in the same reference. Because this method requires the building to be pressurized uniformly from floor to floor, it can only be applied to buildings with non-openable or no windows.

TEST

The performance of the smoke control systems was checked by taking measurements of pressure differences across various separations to determine the air flow pattern in the building and particularly across the designated fire floor enclosure. In some cases, smoke candles were ignited on the fire floor to determine the pattern of smoke flow in the building. Pressure differences were measured with a pressure transducer having a sensitivity of about 0.5 pascal (0.002 in. of water). Flow velocities through damper openings to vent a fire floor were measured either with a deflecting vane type or hot wire anemometer.

Pressure measurements were made throughout the building with the air-handling system operating normally, with it shut down, and with the smoke control system operating. For the sake of brevity, only the results of the measurements taken on the designated fire floor with the smoke control system operating are reported in this paper.

The two test buildings designated as Buildings A and B were constructed between 1970 and 1973. Both use the basic building pressurization method, but they differ in the way the venting of the fire floor is achieved. All outdoor air for pressurization is supplied to the floor spaces through the central air-handling systems except in Building A where part of the outdoor supply air was diverted to the elevator shafts which served as an air distribution duct to the various floors.

RESULTS—BLDG. A

Building Profile

Occupancy: University;
No. of floors: basement and 22 stories above ground;
Floor dimension: 22.8 by 28.3 by 3.2 m (75 by 93 by 10.5 ft);
Mechanical room: 22nd floor.

Smoke Control System

Building pressurization:
- One interior supply fan—19 m^3/s (40,200 cfm);
- One perimeter supply fan—14.3 m^3/s (30,300 cfm).

Venting of fire floor:
- Two smoke shafts (three sides of hollow concrete blocks, the fourth side of cast-in-place concrete) with shaft internal area at floor level of 0.42 m^2 (4.5 ft^2) and between floor level of 0.67 m^2 (7.2 ft^2);
- Smoke damper opening at each floor of 0.20 m^2 (2.2 ft^2) for each smoke shaft;
- Each smoke shaft at top mechanical floor connected to horizontal metal duct which terminates at the exterior walls below roof level.

The smoke control system is shown in Fig. 2 and floor plan in Fig. 3. Operation of the system involves the following steps:

a. Automatic actuation of smoke control system with either a smoke detector or pull alarm at each floor;

b. Perimeter system to 100% outdoor air;

c. Interior system to 100% outdoor air, flow diverted to two elevator shafts by means of dampers in duct work located at the top mechanical floor;

d. Shutdown of return air fan;

e. Closure of dampers in branch ducts of return system on the fire floor;

f. Smoke dampers at the top and fire floor opened; all smoke dampers except the one at the top, if required, can be opened independently from the control panel in basement.

TEST RESULTS

Pressures were measured at an outdoor temperature of -4 °C (25 F) with the smoke control system in operation and the fourth floor designated as the fire floor. The results of the measurements indicated that pressures on the fourth floor were lower than those of the floors above and below by 3.7 pascals (0.015 in. of water). The pressure in the pressurized elevator shaft was higher than that of the fourth floor by 13.7 pascals (0.055 in. of water), but the pressures in the stairshafts were lower than those of the fourth floor by 3.5 pascals (0.014 in. of water) for the one stairshaft and 8.9 pascals (0.036 in. of water) for the other. This indicated that there was a possibility of smoke entering these shafts. The amount of building pressurization obtained was 122 pascals (0.49 in. of water). Flow velocities through the open smoke dampers on the fourth floor were 0.79 m^3/s (1670 cfm) and 0.52 m^3/s (1100 cfm) for the two smoke shafts or a combined exhaust rate of 2.27 air changes per hour, which would be inadequate to prevent possible fouling of the stairshafts in the event of fire.

A separate series of tests was conducted with an outside temperature of (18 °C (65 F) to check the leakage of the smoke shafts. With the floor

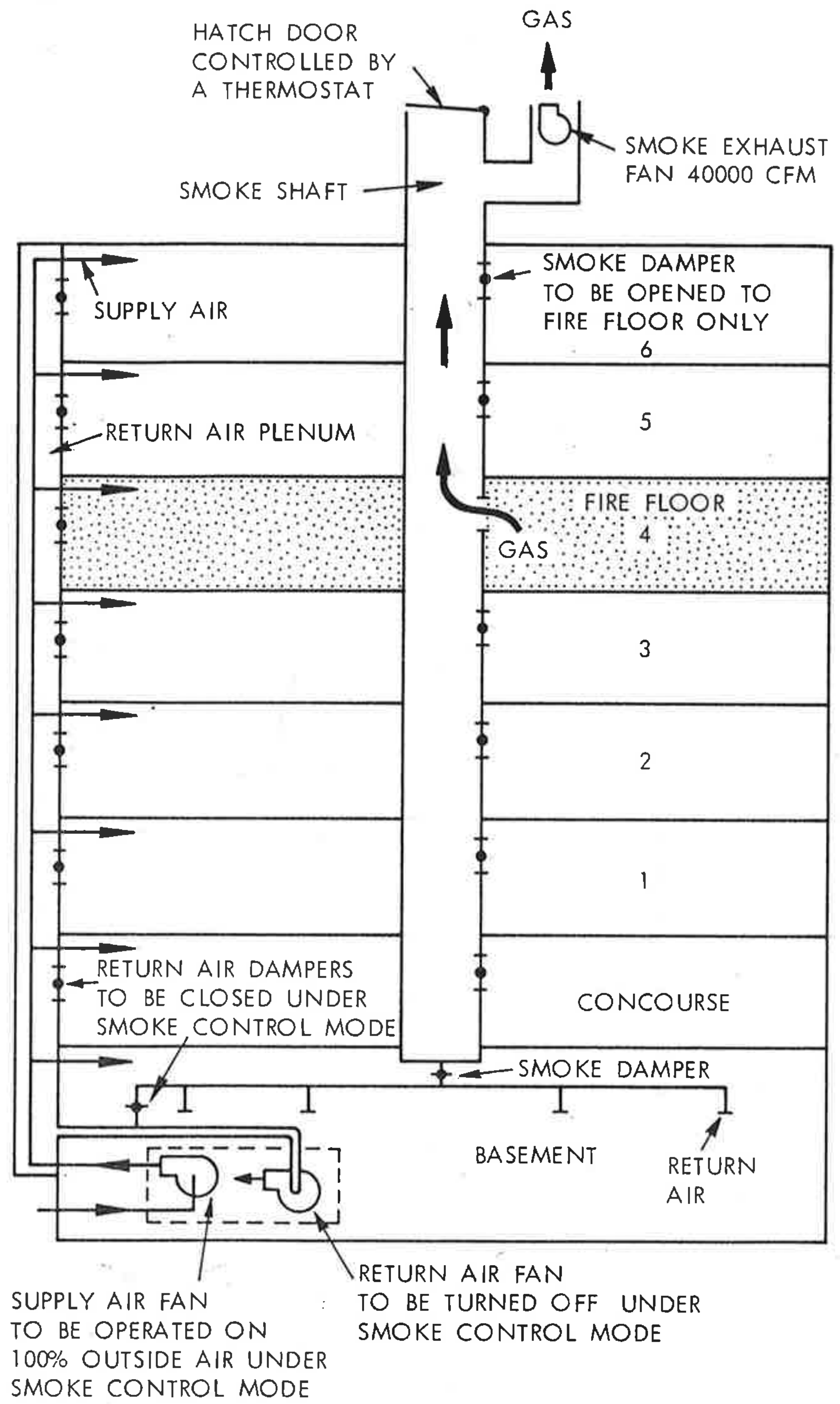

Fig. 4 Smoke control system —Building B

spaces pressurized to 77 pascals (0.31 in. of water) and the smoke dampers open at the top only, flow velocities were measured near the top of the two smoke shafts. From these measurements, the rates of air flow were calculated to be 1.04 m^3/s (2200 cfm) and 0.80 m^3/s (1700 cfm) which represented the rates of air leakage flow from the floors into the smoke shafts. Examination of the smoke shaft construction indicated that the gasketed smoke shaft dampers were relatively airtight, but the wall construction appeared to be leaky particularly at joints between the top of the concrete block walls between floors and the concrete floor slab as well as between the concrete block walls and the cast-in-place concrete walls. Using the average measured pressure differential across the smoke shaft of 22 pascals (0.088 in. of water) and the total leakage flow of 1.04 m^3/s (2200 cfm), the total leakage area for the one smoke shaft was calculated to be 0.29 m^2 (3.1 ft^2) or approximately 0.014 m^2 (0.15 ft^2) per floor which represented 7% of the opening of a smoke damper.

With smoke dampers open at the fourth floor as well as at the top, flow rates at the top of the two smoke shafts were 0.93 m^3/s (1960 cfm) for both. Measured flow rates through the open smoke dampers at the fourth floor were 0.26 m^3/s (550 cfm) for the one and 0.38 m^3/s (810 cfm) for the other smoke shaft or 28 and 41% of the total flow rate respectively.

With the smoke control system operating, the bottom exit door of one of the stairshafts was opened to the outside. The pressure of the stairshaft, which was indirectly pressurized from the pressurized floor spaces, was reduced causing an adverse pressure differential across the stair door at the fourth floor of 25 pascals (0.100 in. of water). When it was also opened, a flow of air from the fourth floor into the stairshaft was felt at the door opening. This indicated that under this condition smoke could, in the event of fire, flow into the stairshaft.

SUMMARY

The tests indicated that the rate of air exhaust through the smoke shaft was not sufficient to decrease the pressures in the vented floor below those of the stairshafts. The rate of air flow through the open smoke damper was about one third of the total rate of flow out of the smoke shaft with the remainder entering the shaft through leakage openings in the walls. Examination of the smoke shaft construction indicated that its poor performance was probably caused mainly by leaky wall construction. Tests also indicated that opening the stair door at the fire floor and the exit stair door on the ground floor at the same time could result in the flow of air or smoke into stairshafts.

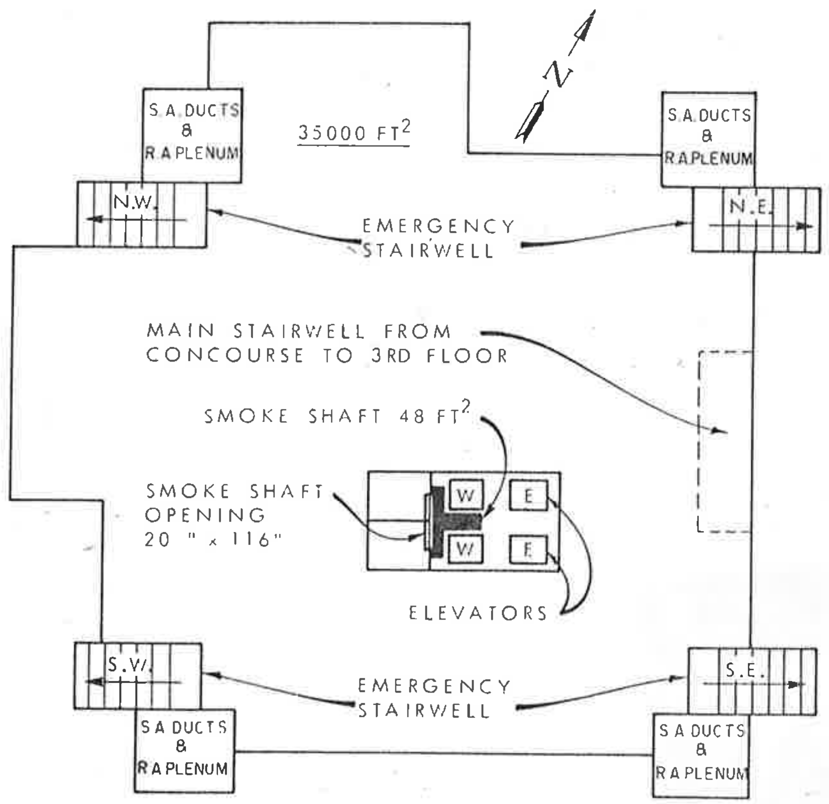

Fig. 5 Typical floor plan—Building B

RESULTS—BLDG. B

Building Profile

Occupancy: Library;
No. of floors: 7 stories above ground and basement;
Floor area: 3250 m^2 (35,000 ft^2);
Floor height: 3.6 m (12 ft);
Mechanical Room: basement.

Smoke Control System

Building pressurization:
- One supply air fan in basement.

Venting of fire floor:
- One T-shaped return air shaft of concrete construction with a total internal cross-sectional area of 4.46 m^2 (48 ft^2);
- Smoke damper opening at each floor of 1.54 m^2 (16.6 ft^2) (two multiple blade dampers);
- An exhaust fan of 18.9 m^3/s (40,000 cfm) at the top of the smoke shaft with a motorized hatch door controlled by a thermostat also located at the top.

The schematic diagram of the smoke control system is shown in Fig. 4 and floor plan in Fig. 5. Operation of the system involves the following steps:

a. Automatic actuation with either a smoke detector or pull alarm at each floor;

b. Main supply air system to 100% outdoor air;

c. Shutdown of return air fan with all return air dampers closed;

d. Smoke damper on the fire floor opens and the smoke exhaust fan activates; and

e. When the temperature inside the smoke shaft rises to about 49°C (120 F), the hatch door at the top of the smoke shaft opens.

Pressures were measured at an outdoor temperature of −8°C (18 F) with the smoke control system in operation and the fourth floor designated as the fire floor. They indicated that the pressures of the fourth floor were lower than those of the four stairshafts by 1.2 to 6.2 pascals (0.005 to 0.025 in. of water) and of the 2 elevator shafts by 1 and 5 pascals (0.004 and 0.020 in. of water). Thus, the operation of the smoke control system for low temperature fire will likely prevent smoke spread from the fire floor to its surroundings.

The rate of air flow into the smoke shaft at the fire floor with the exhaust fan operating was 7.3 m^3/s (15,500 cfm) (2.2 air changes per hour), or 38% of the rated capacity of the fan of 18.8 m^3/s (40,000 cfm) (5.7 air changes/hr). This reduction in exhaust rate at the fire floor was caused by the leakage flow from floors other than the fire floor into the smoke shaft through crack openings in the shaft walls, and dampers that had large gaps between damper and damper frame as well as between damper blades. The rate of flow of air into the smoke shaft at the fire floor with the exhaust fan shut down but with the top hatch open was 8.4 m^3/s (17,800 cfm) (2.5 air changes/hr), slightly higher than the

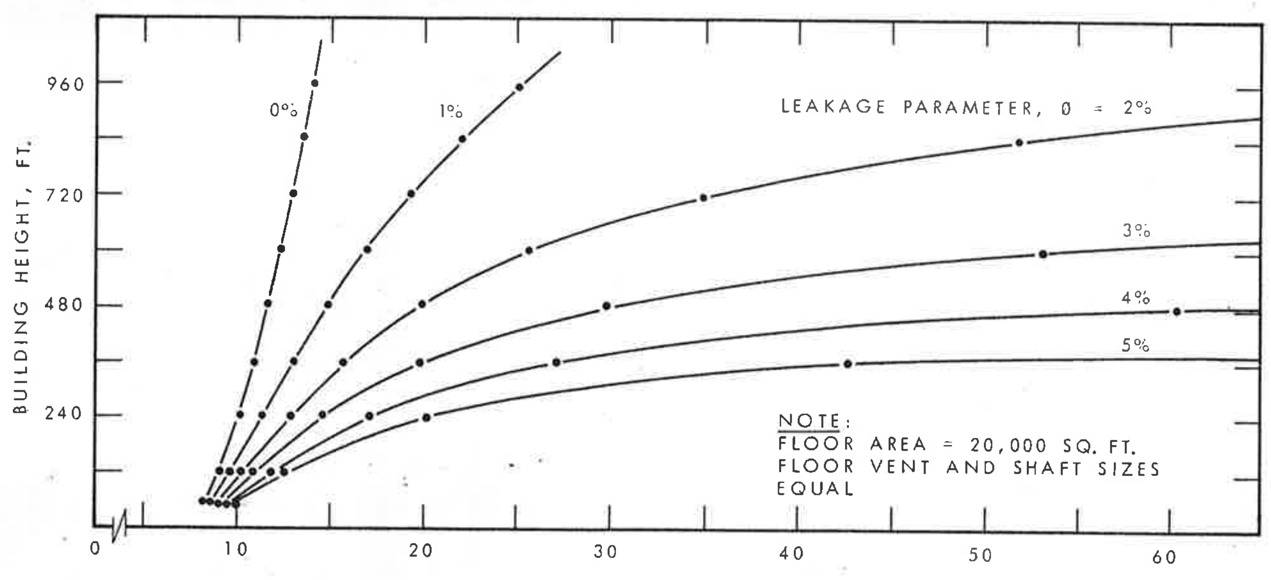

Fig. 6 Effect of leakage parameter on size of smoke shaft

rate with the exhaust fan operating and the hatch shut. The amount of building pressurization was 75 pascals (0.30 in. of water).

Pressure difference readings across the fourth floor stair door indicated that opening the exit door at ground level caused a reduction in the stair pressures as in Building A and a consequent reversal in the direction of leakage flow across the stair door; *i.e.*, from the fire floor into the stairwell. When the stair door at the fourth floor was also opened, the measured air flow rate through this door into the stairshaft was 3.35 m^3/s (7100 cfm).

Eight 3-minute smoke candles were ignited at the fire floor, two in each corner. Observation of smoke movement indicated that with all doors closed no smoke entered either the stair or elevator shafts at the fourth floor. When both the exit door and the fourth floor stair door of one of the stairwells were opened, however, significant amounts of smoke entered this stairwell.

SUMMARY

Both the pressure measurements and smoke test demonstrated that the smoke control system is effective in preventing smoke spread from the fire floor to its surrounding areas when there is no direct connection to the outside via the exit routes. With direct connection to the outside, as is the case of a stairwell with both the exit door and the stair door of the fire floor open, however; smoke contamination of the stairwell can be expected. As for Building A, the leakage flow into the smoke shaft resulted in a significantly lower exhaust rate at the fire floor than expected.

CODE CHANGES

Tests on the smoke control systems of two aforementioned buildings indicate that:

- The performance of the smoke shaft in venting the fire floor can be seriously impaired by the extraneous leakage flow into the smoke shaft through the shaft wall construction from floors other than the fire floor; and
- There is a likelihood of smoke contamination of the stairshaft when the exit door and the door on the fire floor of the same stairshaft are opened at the same time (Fig. 1e).

To correct these shortcomings, requirements for the building pressurization method were altered as follows:

- A new table for selecting the smoke shaft size was introduced based on Ref. 3, which takes into account air leakage through the shaft wall. Fig. 6 shows the required vent and shaft area for a given building height and leakage parameter. The latter is expressed as a ratio of leakage area of shaft per story to an open vent area. It shows that the required vent size increases rapidly with an increase in the leakage parameter and also with the building height. This leakage parameter must also be taken into account for the design of mechanical venting.[4] Good workmanship is essential in achieving a relatively airtight smoke or exhaust shaft for effective venting. Where the return air system is modified to act as a smoke exhaust system it is essential that all dampers except the one at the fire floor close tightly, otherwise the exhaust rate at the fire floor would be less than expected.
- To reduce the possiblity of smoke flow into the stairshafts, they are to be pressurized directly with a supply air rate of 0.14 m^3/s (300 cfm) per story. Also the supply air rate to pressurize the building must be modulated in accordance with the outside air temperature to reduce the pressure difference between the vented floor and outside at grade level for summer conditions.

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