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Analysis of Smoke Shafts for Control of Smoke Movement in Buildings

Smoke migration as a result of fire in a building is potential hazard to life, particularly for occupants in a tall building where evacuation is difficult. Computer studies of smoke movement[1,2,3,] have indicated that, with a fire in a lower story and with outside temperatures lower than inside, smoke can, by the mechanism of stack action, quickly fill the elevator and stairwell shafts and upper stories. Computer and field studies[4] were conducted on the application of top and bottom venting to vertical shafts such as elevators, stairwells and service shafts to prevent this occurrence.

This paper deals with the performance of "smoke shafts" that are sometimes proposed as a means of reducing both the level of smoke concentration on the fire-floor and smoke transfer to other stories. The smoke shaft as defined in this paper is a vertical shaft of noncombustible construction extending from the bottom to the top of the building with openings at the top to outside and with openings in the walls of the shaft at each story. These openings are assumed to be sealed with dampers. In the event of fire, only the dampers on the fire-floor and the top outside damper are opened to exhaust smoke from the fire-floor to outside. The movement of air and smoke through the shaft depends solely on stack action. The "smoke tower" is a special application of the smoke shaft for the purpose of maintaining interior stairwells smoke-free and is required by some building codes.[5]

MATHEMATICAL MODEL

The mathematical model for this study is essentially the same as the one described in Ref 1. The basic components are illustrated in Fig. 1 for a 3-story building. Major separations are exterior walls, walls of vertical shafts, and floors. Leakage areas in the major separations/story are lumped and represented by orifice areas A_w, A_s and A_f. The value of A_s represents the leakage areas of the various service shafts in the building. A 2nd shaft was included to represent a smoke shaft, with vent openings in the wall of the shaft at each story and at the top of the shaft to outside, normally closed with dampers allowing no leakage. In most of the calculations the openings to each story and at the top were assumed of equal size for reasons of convenience.

The value of outside absolute pressure P_{01} (Fig. 1) is taken as normal atmospheric pressure. Outside air pressures at other levels depend on the density of outside air assuming no wind. Inside pressures in the various stories, P_f, are interrelated by the weight of the column of inside air between levels and the pressure drop across the intervening floors. Inside pressures at various levels in the shaft, P_v and P_s, are interrelated only by the weight of the column of shaft air, assuming no friction pressure drop in the vertical shaft and in the smoke shaft.

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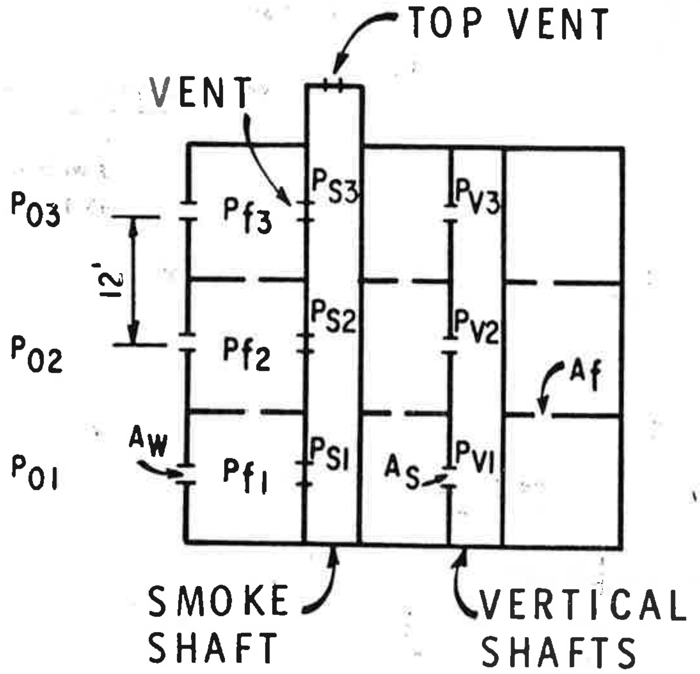

Fig. 1 Mathematical Model.

The problem entails determining the values of inside pressures with which a mass flow balance can be obtained for each story and for the vertical shafts. A computer program was formulated using an iterative technique to solve for all unknown inside pressures. It was designed to permit variation in the number of stories, in the size of various equivalent orifice areas, and in the values of outside and inside air densities.

In the study of smoke movement in tall buildings,[1] a 20-story model building (plan dimension 120 ft sq) was used to investigate the relative influence of a number of factors governing smoke movement in buildings. The equivalent orifice leakage areas for the 20-story model building were based on air leakage measurements in 4 tall office buildings.[1] For this study, similar values of equivalent orifice leakage areas were assumed and are as follows:

$$A_w : A_s : A_f = 2.5 : 5.0 : 3.75 \text{ sq ft}$$

These leakage areas are for each story and, for most of the calculations, are assumed to be the same for all stories.

STACK ACTION

Fig. 2 shows the pressure difference pattern across the major separations of a 20-story model building caused by stack action with an outside temperature of 0 F. All dampers in the smoke shaft are closed. Because the changes in absolute pressure with height, both inside and outside the building, are much greater than the resultant pressure differences across major separations, it is difficult to indicate the values of these differences on an absolute pressure plot. Fig. 2 was constructed, therefore, with the outside pressure line drawn to an arbitrary, but convenient, slope. The inside pressure lines were then referenced to it, using the computed pressure differences with the pressure difference scale shown on the figure.

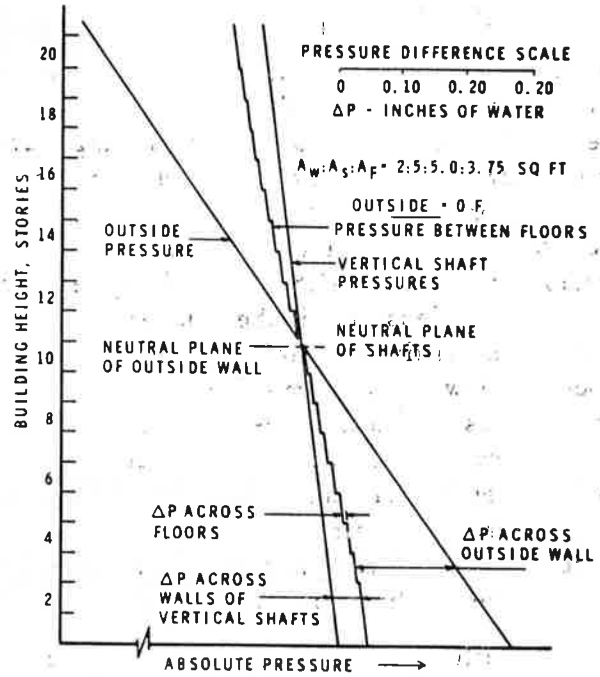

Fig. 2 Pressure Pattern Caused by Stack Action.

Fig. 3 shows the resultant air flow pattern caused by stack action as indicated by the pressure difference pattern given in Fig. 2. Air flows into the building through the outside wall below the level of the neutral pressure plane, up through floors and vertical shafts, and out through the exterior wall above the level of the neutral pressure plane. The total infiltration rate into the building is 19,730 cfm with 19,070 cfm into the vertical shafts and with the remainder through openings in the floors. Because of the series flow resistance represented by floor openings, the air flow rate up through floors is small and most of it occurs in the vertical shafts. If smoke is assumed to follow the air flow pattern shown in Fig. 3, smoke migrates from any fire-floor below the neutral plane into stories above through the vertical shafts.

OPERATION OF SMOKE SHAFT

Under the conditions illustrated in Fig. 2, the pressure in the building is higher than that outside at the top. With a smoke shaft in the building, having an opening to outside at the top and openings to the various stories sealed, the pressure in the shaft at the top is equalized with outside; at all lower levels in the shaft, which is at building temperature, pressures are less than in the adjacent spaces. If, in the event of fire the shaft is opened to the fire-floor, air flow occurs from it into the smoke shaft, and the pressure on the fire-floor is reduced. If the pressure on the fire-floor were reduced below that in the other vertical shafts at the same level and in the story above, air would flow from these regions to the fire-floor and smoke transfer to other parts of the building would not occur.

Fig. 4 illustrates the pressure pattern for this condition for the 20-story model building with a fire in the 2nd story. The air temperature in the smoke shaft and the fire-floor were assumed to be at 75 F. With the smoke shaft in operation, the floor and vertical shaft pressures are decreased at all levels. In the 2nd story, the pressure is approximately equal to the vertical shaft pressure indicating negligible air flow into the fire-floor from the vertical shafts.

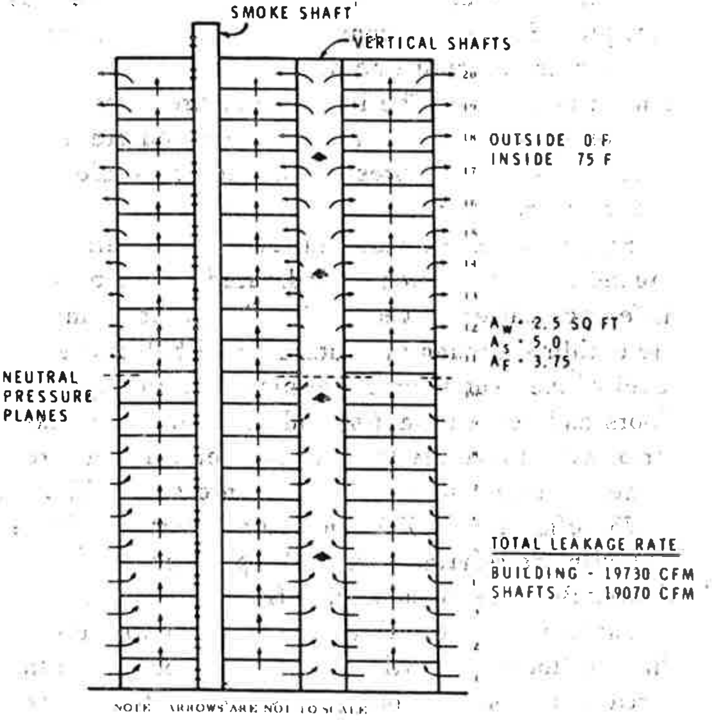

Fig. 3 Airflow Pattern Caused by Stack Action—Smoke Shaft not in Operation.

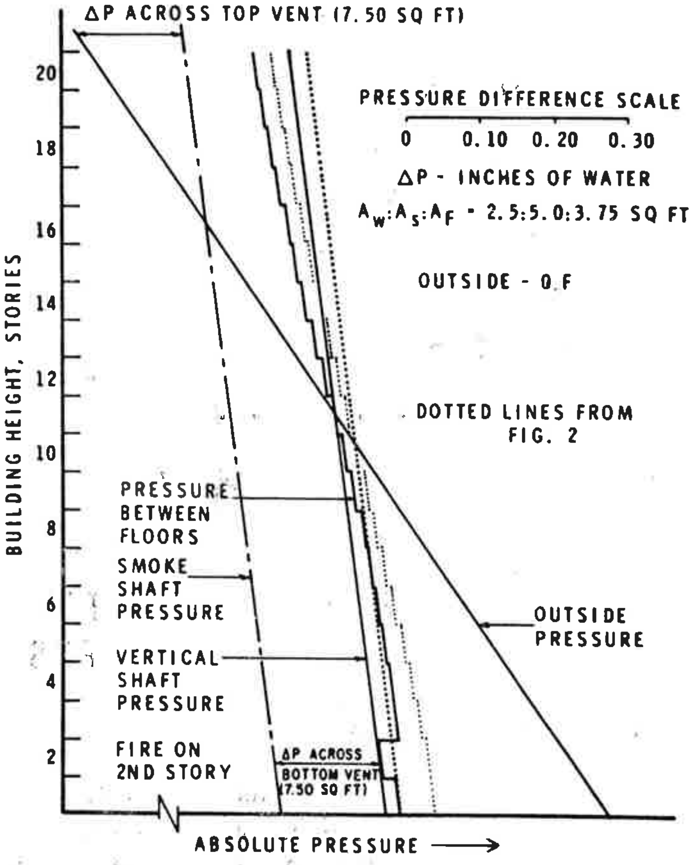

Fig. 4 Pressure Pattern Caused by Stack Action With Smoke Shaft in Operation.

The size of opening required to achieve this condition is 7.50 sq ft based on openings of equal size in the smoke shaft at the 2nd story and top. The pressure in the fire-floor is lower than in the stories above and below, indicating that the direction of air flow is into the fire-floor from these stories. The resultant air flow pattern with the smoke shaft in operation is illustrated in Fig. 5. It is seen that the direction of air flow across the fire-floor enclosure is into the fire-floor and out through the smoke shaft; thus, in the event of fire, smoke migration into upper stories is prevented.

With openings of equal size in the smoke shaft at the 2nd story and at the top, the total pressure difference available for venting smoke is distributed equally across the 2 openings. For the example in Fig. 4 the sum of these is 0.27 in. of water and the calculated rate of air flow into the smoke shaft is 6660 cfm. This is the rate of air exhaust from the 2nd story required to prevent air flow from it into vertical shafts and into adjacent stories; a similar air flow pattern would be obtained with an exhaust fan of this capacity.

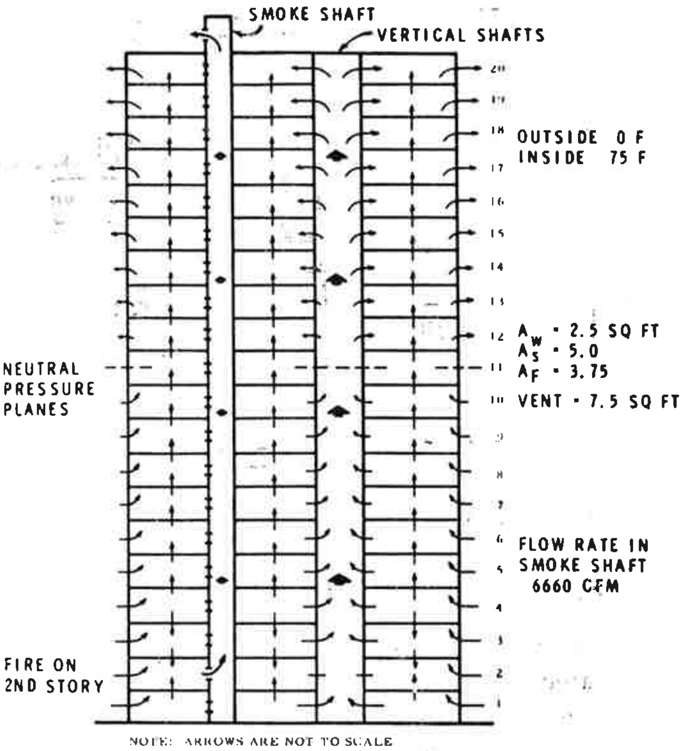

Fig. 5 Airflow Pattern Caused by Stack Action With Smoke Shaft in Operation.

If the opening at the top is larger than that in the fire-floor, the smoke shaft pressure is decreased. Conversely, with the top vent smaller than the vent in the fire-floor, the smoke shaft pressure is increased. In the extreme, the smoke shaft pressure could exceed that in upper stories, causing smoke flow from the shaft into the adjacent spaces through leakage openings around the dampers and in the wall of the smoke shaft.

The vent size needed to prevent smoke transfer from the fire-floor to other stories decreases as the height of the fire-floor above ground increases. Stories at or near ground level therefore establish minimum vent size requirements. Neglecting friction pressure loss in the shaft, the minimum vent sizes were found to be independent of building height, and dependent on the leakage areas of the major separations. With vent openings in the smoke shaft of equal size at the top and at the fire-floor and with ratios of equivalent leakage areas equal to those of the 20-story building ($A_w : A_s : A_f = 1.0 : 2.0 : 1.5$) the required vent size is approximately 3 times the leakage area/story of the outside wall. As building height increases there is a corresponding increase in the amount of air exhausted through the smoke shaft from a fire-floor near ground level. In the calculation of vent sizes, pressure drop in the smoke shaft due to friction was neglected. In practice, it would be necessary to account for this in determining the cross-sectional area of the shaft or the minimum required vent sizes, or both.

The required vent size is independent of inside-outside temperature difference. The smoke shaft ceases to function when outside temperature is equal to or greater than inside temperature, but under these conditions there is less tendency for smoke transfer from story to story.

It is sometimes suggested that an existing shaft, such as an elevator or stairwell, might be used as a smoke shaft. The performance of a 1-car elevator shaft as a smoke shaft was determined for the 20-story model building. A leakage area/story of 1.0 sq ft (0.5 for elevator door and 0.5 for wall) was assumed for this shaft. Fig. 6 illustrates the pressure distributions with a vent opening of 7.50 sq ft at the top of the shaft and at the 2nd story. This vent size is inadequate because of the large leakage area of the shaft in each story. The 2nd story pressure is higher than the pressure in the other vertical shafts and allows flow of smoke into them. Smoke shaft pressure is also higher than in adjacent

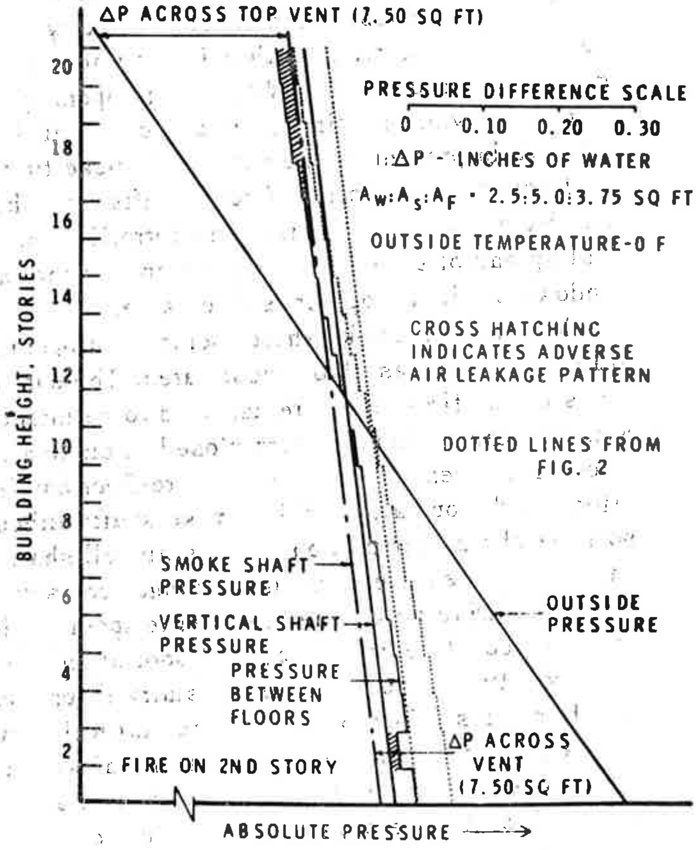

Fig. 6 Pressure Pattern Caused by Stack Action and One-Car Elevator Shaft as Smoke Shaft.

spaces from the 15th to 20th stories, allowing transfer of smoke from the smoke shaft into them. A larger vent size would be required for an elevator shaft to perform adequately as a smoke shaft. The minimum size of top vent required for the model building was computed to be 13.0 sq ft, with an opening of the same size to the 2nd story.

In the examples illustrated in Figs. 4 and 6, it was assumed that air tightness of the exterior walls was unaltered during the fire. It is not unusual for breakage of windows to occur on the fire-floor, either as a result of exposure to the fire or fire-fighting tactics. With a large opening in the exterior wall of a fire-floor, air pressure in the fire-floor tends to equalize with that of the outside at the same level. If this happens at lower levels, the pressure in the fire-floor rises and the potential for air flow from the fire-floor to other parts of the building increases.[1] Assuming an opening of 20 sq ft in the outside wall of the 2nd story (fire-floor) of the 20-story model building, a smoke shaft with vent area of 7.50 sq ft has little influence on the fire-floor pressures and is inadequate to prevent air flow from it into vertical shafts and into stories above and below. The rate of flow into the smoke shaft increases from 6660 to 8450 cfm. The rate of air flow into the vertical shafts at the 2nd story, however, is only slightly less than it is without the smoke shaft in operation. With a large opening in the outside wall of a fire-floor, a smoke shaft is not effective in preventing the spread of smoke from the fire-floor to upper stories. Smoke shafts may, therefore, have serious limitations in controlling the vertical spread of smoke from interior spaces that have windows or similar openings to outside.

The effect on smoke shaft operation of opening stairwell doors was also investigated. The outside walls on the fire-floor were assumed to be intact. With all other stairwell doors closed, including that to outside, opening a door on the fire-floor has little effect on the operation of the smoke shaft, although some smoke contamination of the stairwell shaft can be expected due to air interchange across the open door arising from the elevated temperature in the fire-floor. Opening a stairwell door at an upper level results in a lowering of the stairwell pressure, which induces a flow of air into the stairwell shaft from a fire-floor on a lower level. If a stairwell door on the fire-floor were also open, the rate of air or smoke flow into the stairwell would be greatly increased.

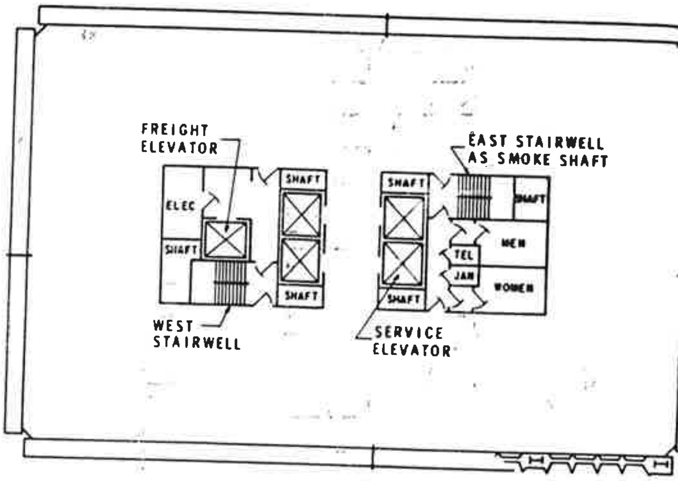

Fig. 7 Floor Plan of Test Building.

FIELD MEASUREMENTS

To check the performance of smoke shafts as indicated by computer studies, pressure measurements were made on a 17-story building using one of the 2 stairwells as a smoke shaft. The floor plan of the building is shown in Fig. 7. The stairwells are provided with 2 doors at each story and with a roof hatch at the top. The east stairwell was arranged to operate as a smoke shaft for fire on the 3rd story by opening the roof hatch (11.4 sq ft) and the 3rd story stairwell door (20.0 sq ft). Pressure difference readings were taken between the 2nd and 3rd stories, between the 4th and 3rd stories and across the elevator and west stairwell doors on the 3rd story both before and during the smoke shaft simulation. Measurements were also taken with 5 small exterior casement windows (total area of 12.8 sq ft) open on the 3rd story. Outside temperature was 17 F. The results of pressure measurements are given in Table I.

With all outside windows closed, the normal air flow pattern across the 3rd story enclosure caused by stack action was from the 2nd to the 3rd story and from the 3rd to the 4th story through the floor construction, and from the 3rd story into the elevator and stairwell shafts. With the east stairwell acting as a smoke shaft, the direction of flow through the floor construction between 3rd and 4th stories and across the west stairwell and elevator doors on the 3rd story was reversed. The direction of air flow was therefore into the 3rd story from adjacent spaces and out through the smoke shaft.

With the east stairwell door and the roof hatch closed, opening the windows caused an increase in

TABLE 1

PRESSURE DIFFERENCE MEASUREMENTS ON 3RD FLOOR OF A 17-STORY BUILDING WITH EAST STAIRWELL AS SMOKE SHAFT

LOCATION OF MEASUREMENTS	WITHOUT SMOKE SHAFT		WITH SMOKE SHAFT	
	WINDOWS CLOSED	WINDOWS OPEN	WINDOWS CLOSED	WINDOWS OPEN
between 2nd and 3rd floor	0.001	−0.090	0.017	−0.040
between 4th and 3rd floor	−0.009	−0.115	0.011	−0.060
west stairwell door on 3rd floor	−0.013	−0.125	0.004	−0.070
west elevator door on 3rd floor	−0.009	−0.130	0.005	−0.075

Notes: Pressure difference in in. of water
Readings referenced to 3rd floor
+ reading : flow into 3rd floor
- reading : flow from 3rd floor
Outside temperature : 17 F

the 3rd story pressure resulting in a downward flow of air from the 3rd to the 2nd stories and an increase in the flow rates from the 3rd to the 4th stories and from the 3rd story into the elevator and stairwell shafts. These effects have already been noted.[1] With the east stairwell arranged as a smoke shaft, the flow pattern across the 3rd story enclosure was unaltered, although a reduction in pressure difference and, hence, flow rates occurred. This confirms that the smoke shaft is not effective in preventing the spread of smoke in a building when there are large openings to outside on the fire-floor.

SMOKE-PROOF TOWER

A smoke-proof tower is specified in some building codes to prevent smoke contamination of stairwells. It consists of a vestibule between each story and the stairwell with an opening to outside in one of the walls of the vestibule. Where it is difficult to vent the vestibule to outside as in the case of a stairwell located in the core of a building, the vestibule is vented to a vertical shaft extending from grade to top of the building. This vertical shaft is essentially a smoke shaft as described previously.

The performance of a smoke tower for the protection of interior stairwells was investigated with the computer model of the 20-story building. The computer model was modified to simulate a combination of stairwell, vestibule and smoke shaft as shown in Fig. 8. Assuming a fire in a 2nd story and a vent area in the smoke shaft at 2nd story and at the top of 7.50 sq ft as before, several cases were investigated. The outside temperature was assumed to be 0 F.

With all vestibule and stairwell doors closed, the direction of air flow is from the 2nd story and stairwell into the vestibule and thence to the smoke shaft, thus preventing spread of smoke into the stairwell. During the course of a fire, it might be expected that some of the doors would be open for fire fighting and evacuation. With the vestibule door open to the fire-floor the operation of a smoke tower is essentially the same as that of a smoke shaft as described previously, and similar limitations therefore apply; that is, with a large opening in the exterior wall on the fire-floor or with open stairwell

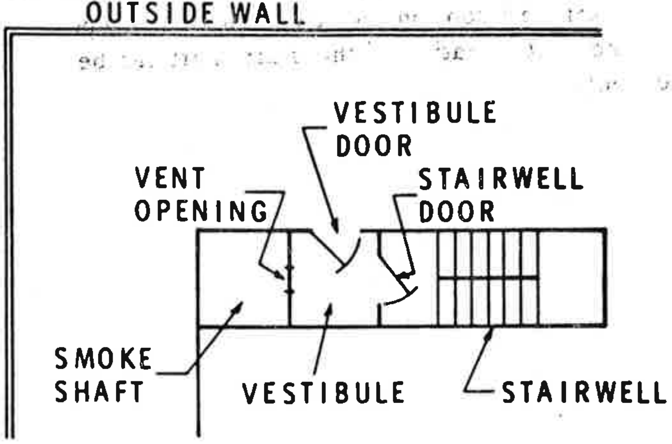

Fig. 8 Smoke Tower.

and vestibule doors on upper floors, smoke entry into the stairwell can be expected. The amount of smoke entry into the stairwell is increased if the 2nd story stairwell door is also open.

With the stairwell door at the 2nd story level open and the other doors closed, the effect of the open smoke shaft vent is to lower the pressure in the stairwell below that in upper stories and thus to induce air flow from them into the stairwell through the various vestibules. If these upper stories were fouled with smoke as a result of flow in vertical shafts some contamination of the stairwell would result. To minimize smoke contamination of the stairwell it is necessary to minimize opening of vestibule and stairwell doors of the smoke tower.

SUMMARY

The performance of smoke shafts was investigated for a building under the influence of stack action, with outside temperatures lower than inside. By reducing the pressure in the fire-floor relative to adjacent spaces the smoke shaft can induce air flow from these spaces into the fire-floor and out through the smoke shaft. In this way, the spread of smoke into vertical shafts and upper stories is prevented. Neglecting friction pressure loss in the shaft, the required vent size is independent of building height and is approximately 3 times the leakage area/story of the outside wall. Where the exterior wall can be expected to remain intact, as in the case of a windowless building, a smoke shaft can be effective in limiting smoke transfer to upper stories. If windows on a fire-floor are broken, however, the pressure in the fire-floor approaches that of the outside and the smoke shaft is no longer effective in preventing the spread of smoke. If a stairwell door on an upper story is open, the stairwell pressure is reduced below that of the fire-floor and if a stairwell door on the fire-floor is also open, smoke contamination of the stair shaft can be expected.

The smoke-proof tower for interior stairwells can be effective in preventing contamination of a stair shaft in the event of fire provided that the vestibule and the stairwell doors on the fire-floor and upper stories are closed.

ACKNOWLEDGEMENTS

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DISCUSSION

J. B. SEMPLE, (Air Balance Inc., West Conshohocken, Pa.): Have you had any opportunity to do any work under summer conditions on the operation of these shafts?

MR. TAMURA: The operation of a smoke shaft during the winter was discussed in the paper. During the summer, with little or no building stack action, thermal expansion as a result of temperature rise in the fire-floor is an important mechanism by which smoke spreads from the fire-floor to the various parts of the building. The rate of smoke flow out of the fire-floor enclosure by thermal expansion depends on the rate of temperature rise and on the leakage openings of the fire-floor enclosure. The rate of flow can be reduced by venting the fire-floor to outside with a smoke shaft. It can also be reduced by venting the fire-floor with a large opening in the exterior wall.

With the model building described in the paper, the effectiveness of smoke shaft in venting the fire-floor was investigated. It was assumed that a mean temperature in the fire-floor of 1000 F was reached in 30 min during which time two floor volumes of gas left the fire-floor. A mean temperature of 250 F inside the smoke shaft was also assumed. Under this condition, with the smoke shaft in operation, the direction of flow across the fire-floor enclosure is reversed, with air flow into the fire-floor enclosure from the adjacent areas and into the smoke shaft to outside.