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Smoke Movement in High-Rise Buildings

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Please note

Smoke generated by fire has long been recognized as a potential threat to life. A fatality as a result of fire is often due to the effect of smoke rather than the effect of heat.

Fire safety in buildings is currently provided by the use of fire resistive construction and compartmentation, and by limitations on the use of combustible materials and materials that have high flame spread ratings (**CBD 11**, **CBD 31**, **CBD 33**, **CBD 45**, **CBD 53** and **CBD 71**). These and other measures are reflected in building and fire codes. They are directed primarily towards limiting the size of a fire, with the final objective of minimizing hazard to life and property.

By confining a fire to a specific area fire resistive construction not only limits its size but also limits the amount of smoke. Fire resistive compartments, however, do not prevent the spread of smoke from the fire compartment to adjacent areas, because the enclosure constituting a compartment is not air or smoke tight. A fire may be confined to a specific area, but smoke can migrate to various parts of a building and is therefore a potential threat to occupants far removed from its source as well as to occupants in the immediate vicinity. Cases have occurred where occupants on floors far removed from the fire floor have lost their lives.

In the event of fire it is customary to evacuate buildings in order to minimize life loss, and occupants of low buildings can be evacuated in a relatively short time. The time for total evacuation by stair shafts, as currently provided, however, increases with building height and can exceed one half hour for a typical building over 20 storeys high(1). In very tall buildings, many occupants would be physically incapable of negotiating the stair shafts from the upper floors to the ground level, particularly under emergency conditions. Although smoke spread is a factor that must be considered for low buildings, it takes on much more serious significance for high-rise buildings because escape routes may become untenable before the occupants can be evacuated. This Digest discusses the causes and the characteristics of smoke movement in buildings.

Characteristics of Smoke

Two important features of smoke are that it contains toxic products of combustion and reduces visibility. The two factors are generally related. Dense smoke is usually highly toxic and reduces visibility substantially.

The physical properties of a smoky atmosphere are similar to those of a normal atmosphere; the main constituent for both is nitrogen. Oxygen and carbon dioxide may vary about 10 per cent from normal amounts without substantially affecting the physical properties of the atmosphere. The concentration of particulate smoke, even under conditions of very low visibility, is not sufficient to alter the characteristics of an atmosphere enough to affect its movement. It can be assumed, therefore, that smoke will probably follow the over-all air movement within a building.

Mechanism of Smoke Movement

Although a fire may be confined within a fire resistive compartment, smoke can readily spread to adjacent areas through such air leakage openings in the enclosure of the compartment as cracks, openings around pipes, ducts and doors. These leakage openings will permit a substantial smoke flow even with quite small pressure differentials. The principal factors that cause smoke to spread to areas outside a fire compartment are:

1. temperature effect of fire,
2. weather conditions, particularly wind and temperature,
3. mechanical air handling system.

Molecular diffusion is significant as a mechanism for dispersing gases (odours, etc.) within buildings, but in comparison with the various other mechanisms that create smoke movement it may be ignored.

Temperature Effect of Fire

Heat generated by fire results in increased gas temperature. This causes smoke to move outside the fire compartment by two mechanisms: thermal expansion and stack action. With any increase in the temperature of a fire compartment, there is a corresponding increase in the volume of gas. Assuming that a fire compartment leaks sufficiently to preclude an appreciable buildup of pressure, it follows that the gas volume increases approximately in proportion to its absolute temperature. With a temperature rise from ambient to 1000°F in the fire compartment, the volume of gas is increased to approximately three times its original volume and approximately two thirds of the original gas in the fire compartment is forced outside it. This flow of gas out of the compartment due to thermal expansion will continue as long as the temperature in the compartment is rising.

When the fire temperature reaches a steady value, however, the gas is no longer expanding and the principal mechanism by which smoke moves out of the compartment is stack action (the same mechanism that prevails in heated buildings in winter (**CBD 104**, **CBD 107**)).

With fire in a single floor area, stack action acts over one floor height. Air flows through leakage openings in the walls of the fire compartment at low levels and smoke flows out of the compartment at upper levels to adjacent areas. With fire in a vertical shaft such as an elevator and service shaft, stack action involves the whole height of the shaft and its effect is therefore much greater. Air flows into the shaft from the floor areas in the lower portion of the building and smoke flows from the shaft to the floor areas at high levels. This flow pattern induces a downward flow of air in any remaining shafts and through leakage openings in the floor construction (Figure 1). Fire in a shaft, therefore, can cause recirculation of smoke throughout a building.

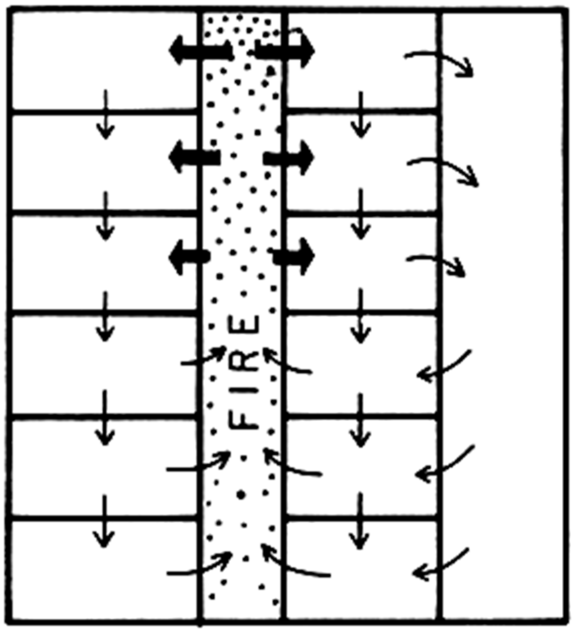

Figure 1. Smoke movement caused by fire in shaft.

A similar flow pattern involving recirculation can result from fire in a floor area when there is a substantial flow of hot gases from the floor area into a vertical shaft. This might happen where a door between a vertical shaft and a fire floor is left open.

Effect of Weather

External conditions can also cause smoke to move from a fire area to various parts of a building. Under certain conditions, wind action can cause smoke to move vertically upward within a building, but its principal effect is to cause air or smoke to move in a horizontal direction towards the leeward and side walls.

Stack action associated with building heating during cold weather (**CBD 104**, **CBD 107**) is another mechanism by which smoke can spread upwards from a fire on a lower floor. Stack action causes air to flow into the building at low levels and out at upper levels. Air flows upwards within the building through openings in the floor construction and through vertical shafts, with most of the upward flow occurring in the vertical shafts. Smoke generated by a fire on a lower floor thus migrates to vertical shafts and hence to upper floors (Figure 2a). With fire in an upper floor there is little tendency for smoke to migrate to other floors as a result of this mechanism, except for the floor immediately above the fire floor (Figure 2b).

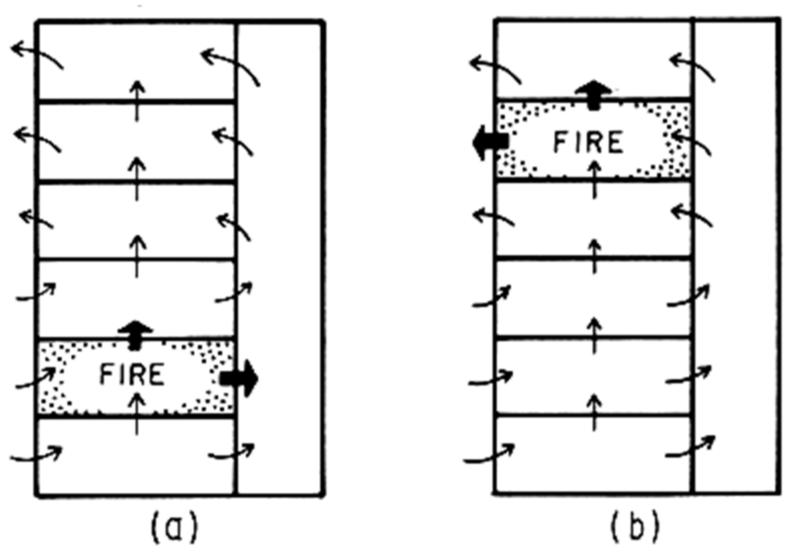

Figure 2. Smoke movement caused by stack action in heated building (a) low-level fire (b) upper-level fire

Under summer conditions, with an outside temperature higher than that inside, the flow pattern is the reverse of that under winter conditions. The air flows are, however, considerably lower because the inside-to-outside temperature difference is much smaller. Smoke movement to various floors under summer conditions is, therefore, due principally to the heat generated by the fire.

Effect of Air-Handling System

An air-handling system can also contribute to smoke migration in the event of fire. It can recirculate smoke throughout a building by the return and supply air systems. For this reason some standards call for a shut-down of all major air-handling systems as soon as excessive smoke or heat is detected in the return air system. With the system off, however, vertical air ducts may still act as additional paths for smoke migration to upper floors.

Smoke Concentration Pattern Caused by Stack Action

Various mechanisms causing smoke movement have been discussed. They usually act in combination during a fire. In considering measures to control smoke movement, therefore, one must evaluate their various effects and consider those that have the greatest potential for smoke spread.

Studies indicate that stack action during cold weather causes the greatest potential for smoke spread within a multi-storey building. Figure 3 shows calculated values of maximum smoke levels in various parts of a building with typical air leakage characteristics, assuming a fire on the first floor of a 20-storey building and an outside temperature of 0°F with no wind. A smoke level of unity is assumed for the fire floor. It is also assumed that the entire floor area is open plan and uniformly polluted. Because of the diluent effect of air leakage flow into the building from stack action, smoke levels above the first floor are less than unity. Under severe fire conditions, a smoke level 1 per cent of that on the fire floor can be considered a critical level for safety of the occupants. In the case considered the entire building is contaminated, with the exception of floors 3 to 10. For steady-state conditions this is the smoke pattern that one can expect under stack action with temperature outside lower than that inside, almost regardless of the magnitude of the temperature difference. The time to reach these values depends on the leakage characteristics of the various compartments and the temperature differences. With greater flow rates during cold weather when pressure differences are greater, the time to reach steady-state values is less and hence the rate of development of smoke contamination is greater.

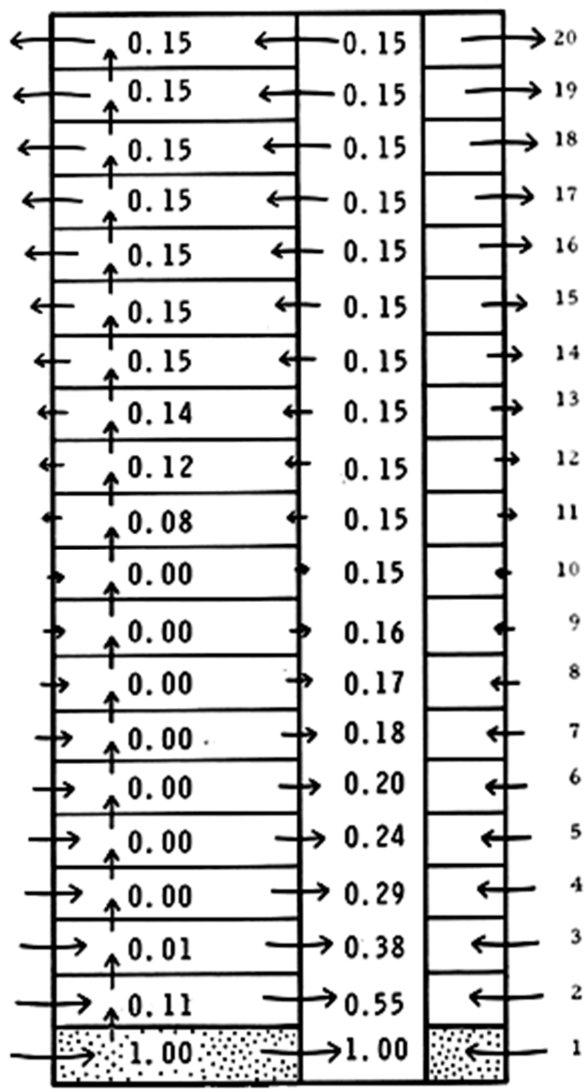

Figure 3. Smoke concentration pattern caused by fire on first floor and stack action; steady state.

If the air leakage characteristics of a building are known, estimates can be made of the time for smoke concentrations to reach critical values throughout the building. Computations for a 20-storey building[(2)], indicate that five minutes after the development of fire on the first floor all of the elevator shaft, the lower part of the stair shaft, and the floor above the fire floor will be untenable. In fifteen minutes the upper eight floors also will have smoke levels above the critical value. After three hours, when steady-state conditions exist, the smoke pattern will be similar to that shown in Figure 3. In this example it should be noted that the time for smoke to reach the assumed smoke level in the fire area is taken as zero. Under some fire conditions development of fire can, in fact, be very rapid.

Over-all rate of air leakage and, hence, the rate of smoke movement in high-rise buildings depends also on the leakage areas in the outside walls and walls of vertical shafts. The example given is for a building with typical air leakage characteristics. Increasing tightness of building components can reduce the rate of air leakage and, hence, the rate of smoke contamination. During a fire the leakage area of the outside wall on the fire floor may be increased by breakage of windows as a result of high temperature.

If this happens at a low level with a building under stack action, the pressure difference across openings into a shaft and across the floor is increased, as is the rate of smoke flow into the vertical shafts and upper floors. A large opening in the outside wall of a fire floor can, however, have a positive value during the development stage of a fire in that it can serve as a vent for expanding gases, thus virtually eliminating expansion as a smoke movement mechanism.

The smoke pattern given in Figure 3 assumes a fire originating on a floor with no compartmentation. If the floor is compartmented, as for apartments, and a fire occurs in one of them, the smoke leaving the fire compartment will be diluted with the air leakage flow from the other compartments before it enters the vertical shafts to upper floors. Compartmentation of floors not only limits the spread of fire but can also limit smoke densities throughout a building as long as the door of the compartment on fire is closed. If it is open, on the other hand, the corridor can reach a smoke level of unity and the smoke pattern in the building can be similar to that associated with a fire in an open floor area.

Conclusion

In the event of fire in the lower levels of a high-rise building, the upper floors and escape routes can become contaminated with smoke very quickly and in less time than is required to evacuate the building. Control of smoke is therefore an important consideration in the design of buildings. A future Digest will discuss the means whereby such control may be obtained.

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