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BUILDING DESIGN AND THE FIRE HAZARD[1]

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ABSTRACT

Building codes cover only the minimum requirements for fire safety and leave ample room for the expertise and conscience of the building designer. Providing life safety starts with securing conditions under which sufficient time is left for the occupants to escape from an incipient fire. It also involves measures that reduce the probability of exposure of the occupants to smoke and ensure their evacuation from the fire-stricken area. The safety of both life and property is served by ensuring the structural integrity of all key elements of the building even in spreading fires, but at the same time employing all available techniques to confine the fire to its place of origin.

Keywords: Building design, design, fire protection, fire safety, building codes.

Nomenclature

- A area, ft^2
- B constant, $= 39.74$ lb R/ft^3 for air and gaseous products of fire
- g acceleration due to gravity, $= 4.17 \times 10^8$ ft/h^2
- G total fire load, lb
- h height, ft
- H height of building, ft
- p pressure, lb/ft h^2
- Δp pressure difference, lb/ft h^2
- P perimeter of building, ft
- q heat flux, Btu/ft^2 h
- T temperature, R (if not otherwise specified)
- U mass flow rate to compartment, lb/h
- V infiltration mass flow rate, lb/h
- W pressurization mass flow rate, lb/h
- z elevation, ft

Greek letters

- α equivalent orifice area, ft^2/ft^2
- β orifice factor, ≈ 0.6, dimensionless
- τ period of fully developed fire, h
- χ pressure factor, dimensionless

Subscripts

- a of outside atmosphere, of air
- c for corridor-room partition
- cr critical
- C for corridor
- E effective
- F of floor
- g of compartment gases
- i of the interior of building
- o at the level $z = 0$
- R for room
- s for shaft-corridor partition
- S for shaft
- U for uncompartmented space
- w for outside wall
- W of window

INTRODUCTION

Of the many topics that could be discussed under this title, only a few deemed to be of primary interest to this audience will be dealt with in this paper.

Buildings with a minimum fire hazard are fire-safe. A fire-safe building can be defined as one for which there is a high probability that all occupants will survive a fire without injury, and in which property damage will be confined to the immediate vicinity of the fire area.

There are numerous, mostly complementary, ways of achieving fire safety, not all of which are related to building design. Those

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that are, concern (1) layout and dimensioning of the building and its constituent parts, (2) provision of safety devices and facilities, and (3) selection of construction materials.

The minimum requirements for safety are dealt with, in law, by building codes. The designer is allowed, however, to use equivalent or better solutions and to choose safer materials. All in all, the level of fire safety in building depends, to a large extent, on the conscience of the designer, and the provision of safety at a minimum cost depends on his expertise.

Three subject areas have been selected to illustrate the role of circumspect design in the provision of fire safety: the growth of fire, the smoke problem, and the fully developed fire. Of these the first two are related mainly to the aspect of life safety, whereas the third is concerned with both life safety and safety of property.

THE GROWTH OF FIRE

At least four out of five fires start from relatively small ignition sources (Berl and Halpin 1976). Whether the small fire dies out or grows into a large fire depends on the conditions in the environment of the source fire. If they are favourable for the growth of fire, "flashover" will ensue and the entire compartment that contains the source becomes involved in fire. Flashover, if it occurs, follows the flaming ignition of a larger object in the compartment usually in 5 to 20 min.

The time of flashover is an extremely important piece of information, because it indicates the maximum amount of time that the occupants have to escape or be rescued. For this reason thorough understanding of the chain of events that connects the ignition of the source item with the flashover has become, in recent years, one of the major objects of theoretical and experimental fire research (Gross 1974; Croce and Emmons 1974; Smith and Clark 1975; Croce 1975; Modak 1976; Quintiere 1976; Emmons 1977).

For some time following ignition, the source item burns in approximately the same way as it would in the open. Then, as flames spread over the surface of the source item, and perhaps to other contiguous items, the process of burning becomes influenced more and more by the environment. Heat is fed back from the surrounding objects, especially from the compartment boundaries, and augments the rate of burning. With increasing rapidity a layer of hot smoky gases builds up below the ceiling. As Fig. 1 shows, intense radiant energy fluxes originating mainly from the hot ceiling and the adjacent smoke layer gradually heat up the contents of the compartment and, upon reaching a level of about 1.7 to 2.1 W/cm^2 (Fang 1975), ignite, in quick succession, all combustible items within; flashover occurs. [Experimental studies (Gross 1974; Hägglund et al. 1974) indicate that the attainment of a temperature of 500 to 600 C by the hot gas layer can also be regarded as a flashover criterion.]

A few fire "scenarios" of practical interest were recently surveyed by Benjamin (1976). He pointed out that combustible wall and ceiling linings may or may not play a substantial part in the chain of events leading to flashover, depending on the total fire load, distribution of the combustible items, and location and size of the source fire. On the one end of the safety scale are densely furnished rooms with large combustible contents (i.e., with high "fire load") and with items of high specific surface (to be discussed). The time to flashover for such rooms is very short, regardless of the nature of the lining materials. On the other end of the scale are the sparsely furnished rooms. For these a combustible wall lining may become the principal path of fire spread and, therefore, the presence or absence of such linings may mean the difference between short flashover time or no flashover at all. Naturally, for rooms lined with combustible materials the location and size of the source fire are of extreme importance. Bruce's experiments (1959) showed that the nature of the walls had very little effect on the time to

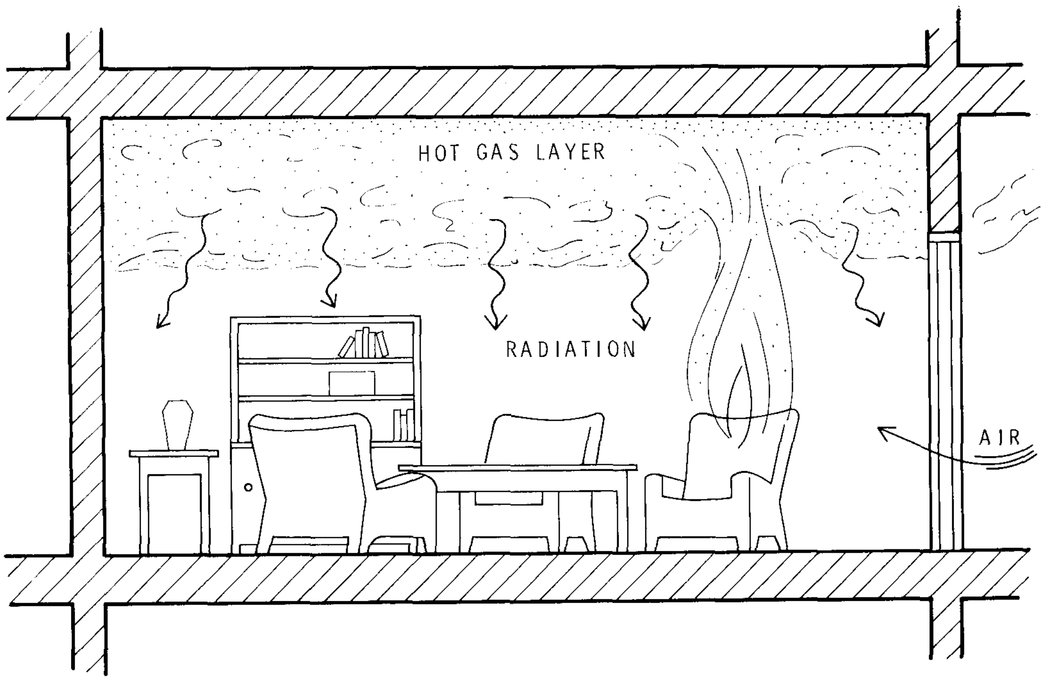

FIG. 1. Pre-flashover fire.

flashover when no combustible item was closer than 18 inches to the walls.

The so-called "oxgyen index" method (Fenimore and Martin 1966; ASTM D2863-74) provides a convenient way of arranging various materials according to their liabilities of becoming sources of fire. (Table 1 gives the oxygen index for a few common materials.) The oxygen index does not, however, reflect the increased or decreased liability associated with the shape, surface texture, and orientation of an object. It is common knowledge that an object with large "specific surface area" (external surface area per unit weight) is more easily ignited than a bulky object. It takes considerable effort to ignite a massive piece of wood furniture, whereas other objects of cellulosic materials, for example cotton fabric or sheets of paper, flame up quite readily.

Unfortunately, there is no reliable test method to date that could be used to predict the burning characteristics of various materials once the fire has grown beyond its incipient stage. Benjamin (1976) documented with data borrowed from a report by Castino et al. (1975) that flamespread ratings derived from standard tunnel tests (ASTM E 84-76a) do not necessarily place the various lining materials in the correct order as far as the hazard of early flashover is concerned. Friedman (1975) noted that some fire-retarded panels, though not readily ignitable, once ignited spread flames just as fast as nonretarded panels.

These findings come as no surprise to those familiar with fire-performance tests. For the sake of ensuring the commensurability of the results, i.e., the ability of arranging the results on a unique quality scale, these tests are conducted under a specified set of conditions which rarely, if ever, coincide satisfactorily with those arising in actual fires. For example, the rate of flame spread is known to depend significantly on the radiant energy flux to the lining material (Alvares 1975; Fernandez-Pello 1977). There is evidence (Tewarson and Pion 1976) that strong energy fluxes,

TABLE 1. *Oxygen index for a few common materials (Hilado 1969, Tsuchiya and Sumi 1974)*

Material	Oxygen Index[a]
Carbon, porous	55.9
Epoxy, conventional	19.8
Foam rubber	16.0
Neoprene	31.0
Polyamide (nylon)	29.0
Polycarbonate	26.0
Polyester (FRP)	18.2
Polyethylene	17.4
Polyisocyanurate foam, rigid	25.9
Polymethyl methacrylate	15.9
Polypropylene	17.4
Polystyrene	18.1
Polystyrene foam	18.8
Polystyrene foam, flame retardant	24.1
Polytetrafluoroethylene (teflon)	95.0
Polyvinyl chloride	46.6
Polyurethane foam, flexible	16.1
Polyurethane foam, rigid	15.3
Urea-formaldehyde	25.8
Wood, white pine	20.9
Wood, sugar maple	21.2
Wood, plywood	19.7

[a] Oxygen index = minimum oxygen concentration, expressed as volume percent, required to support flaming combustion

such as those arising in real-world fires, may completely upset the ranking of various lining materials by standard tunnel tests. If it is realized that the level of thermal radiation is only one of the numerous factors that may have important bearing on the phenomenon of flame spread, one will recognize the problems associated with deriving meaningful but simple performance tests.

The most important requirements that must be followed to prevent fast developing fires are covered in building codes, which regulate what can be built into a building, and fire codes, which control what can be brought into it. Typical items that fire codes are concerned with include movable partitions, floor covering and decorating materials, drapes, and curtains, for use in buildings of dense occupancy. These items must be subjected to various performance tests (Sumi 1975) that will, it is hoped, yield some idea of their propensities for becoming ignition sources and propagating fire.

The building code regulations that have some bearing on the time to flashover are those that restrict the use of combustible lining materials. Conventionally, interior finishes having flame spread ratings higher than 150 are not allowed in buildings of dense occupancy in many parts of North America. Further restrictions are imposed on the flamespread ratings of linings used in exits. A recent addition to building codes requires that foam plastics, which have been known to spread fire much faster under realistic fire conditions than in performance tests, be covered air-tight with nonfoamed linings.

The safety of a building can be improved further by circumspect design. The building designer knows the intended use of the building and, therefore, has at least a rough idea of the types of articles that may be brought into the various compartments upon completion of the building. He can add valuable minutes to the time to flashover by avoiding extensive use of combustible linings in those compartments that are most likely to be furnished with fabric-covered (upholstered) items, or in which clothing articles are kept or stored. He can further heighten the level of fire safety by providing closets and built-in cabinets for the storage of cloth and paper products. In the design of theatres, lecture rooms, atriums, lounges, etc. he can specify slightly elevated or recessed walk-ways or built-in planters along walls that are to be lined with combustible materials, and thus prevent the occupants or interior decorator from placing upholstered furniture close to those surfaces.

In closing this subject, it may be appropriate to mention briefly the sprinkler system, because its chief function is to prevent incipient fires from reaching the flashover stage. Except for buildings with very large uncompartmented spaces, the use of sprinkler system is an optional measure, but its use is often rewarded by the reduction of other building code requirements and by lower insurance premiums. The principles of designing a sprinkler system are well known (Tryon and McKinnon 1969) and will not be discussed here.

THE SMOKE PROBLEM

Fire statistics reveal (Berl and Halpin 1976; HMSO 1971; Thomas 1974) that more people die in burning buildings from inhalation of toxic fire gases than from heat-inflicted injuries. Even in those deaths that are caused by burns, smoke is often a contributing factor; dense smoke obscures the vision of the occupants and prevents them from reaching safety.

Many clauses in building codes relate to facilitating escape from fire-stricken buildings. Regulations cover the width of exits as a function of occupant concentration, distance between exits, access routes to exits, location and illumination of exit signs, and the maximum length of dead-end corridors. In addition, restrictions are gradually introduced on the use of materials that have a propensity for high smoke generation. However, efforts to provide a rational basis for restricting the use of the worst smoke-producing materials are hampered by two difficulties. The smoke-producing characteristics of most materials depend quite substantially on the temperature and oxygen concentration of the surrounding atmosphere (Tsuchiya and Sumi 1974) as well as on the rate of flow of air past the burning object (Gaskill 1973; Robertson 1973); consequently those materials that prove poor performers in laboratory tests may be acceptable under actual fire conditions, or vice versa. The other difficulty is that processes introduced to retard the flame-spreading characteristics of lining materials are often responsible for increased smoke production.

So far there has not been any attempt to restrict the use of materials on the basis of their propensities for generating toxic decomposition or combustion products. The most likely reason is that carbon monoxide, which may be produced by any material as a result of incomplete combustion, is still believed to be the only toxic gas worth consideration. Accumulated data (Sumi and Tsuchiya 1975) indicate, however, that other toxic gases such as hydrogen cyanide, hydrogen chloride, nitrogen dioxide, and sulfur dioxide may be the cause of fire deaths or injuries more often than is commonly believed.

To ensure the safety of the occupants, the installation of fire detectors and fire alarms has been made mandatory in certain buildings, mainly those of high occupant concentration. In addition, in buildings with air circulating systems, the installation of smoke detectors in the main ducts is also required. Detection of smoke in the main return duct is followed by the shutdown of the return fan and by the actuation of the fire dampers of the duct system.

Unfortunately, dispersion of fire gases in a tall building is possible even after shutdown of the air-handling system. The smoke can be carried by natural air currents to far places in the building. There are documented cases of hundreds of deaths caused by smoke inhalation at large distances from the location of fire.

Air currents that disperse fire gases throughout the building develop as a result of the "leakage" of the outside walls of the building, and are induced by temperature differences between the interior and exterior atmospheres. For the latter reason, they are strongest during the winter heating season. Figure 2a illustrates schematically the dominant air currents in a nine-storey office building in the winter (with the air-handling system shut down). The building is shown to consist of four types of spaces: rooms (R), corridors (C), uncompartmented spaces (U), and stairwells and elevator shafts, referred to here jointly as shafts (S). If the leakage characteristics of the outside wall are uniform, the infiltration of air takes place below the mid-height of the building. After passing through various partitions, it enters the shafts, rises to the upper floors of the building, moves toward the outside wall, and exfiltrates to the outside atmosphere. Because of the important role the stacklike shafts play, the phenomenon is often re-

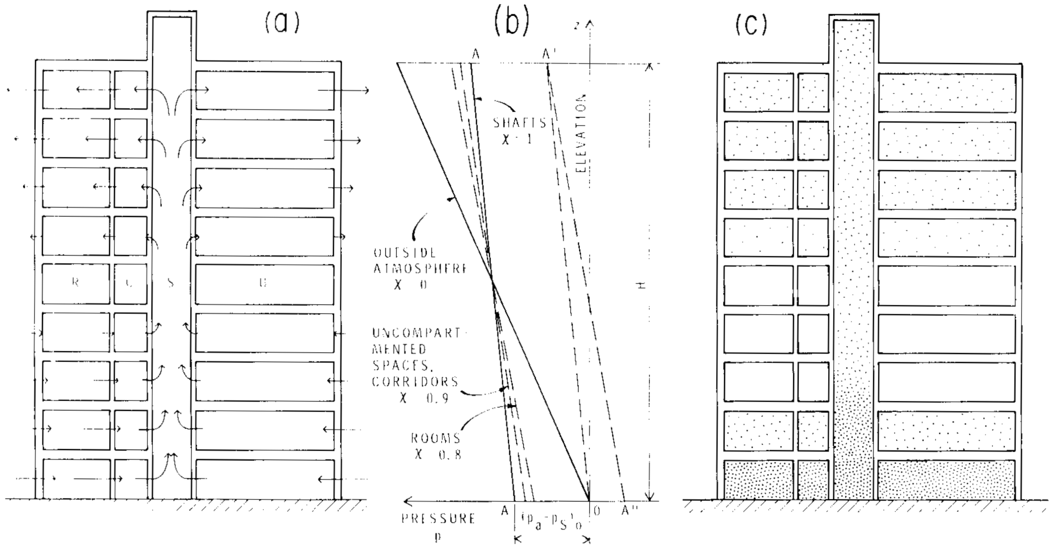

FIG. 2. Illustration of smoke problem in a 9-storey office building (a) Air currents, (b) Pressure distribution, (c) Smoke distribution (fire on first storey).

ferred to as air movement by "stack effect" or "chimney effect." (The small air currents that rise from storey to storey through the ceilings are not taken into account in the present discussion.)

The rate of air flow depends on the leakiness of the outside walls and the various interior partitions of the building. Since the flow through small holes or gaps can be treated as flow through orifices, it is usual to characterize the leakiness of a building element by its "equivalent orifice area," α, which is the aggregate area of (often invisible) holes, cracks, gaps, etc., referred to unit area of the building element. An analysis of the situation illustrated in Fig. 2a requires information on three of these equivalent orifice areas: α_w, that for the outside walls, α_c, that for the corridor-room partitions, and α_s, that for the shaft-corridor partitions.

The direct causes of air movement in a building are, naturally, the pressure differences that exist between the constituent spaces of the building. Experimental studies of heated multistorey buildings (Tamura and Wilson 1966, 1967) indicate that the pressure distribution along the height of a simple multistorey building can be represented by a series of straight lines, as shown in Fig. 2b. (In reality, the lines for rooms, corridors, and uncompartmented spaces show slight discontinuities at the ceiling of each storey.) They can be described by the following equation:

$$p - p_a = -gB(1/T_a - 1/T_i)(H/2 - z)\chi\,, \quad (1)$$

where p_a, the pressure of the outside atmosphere, is

$$p_a = -(gB/T_a)\,z\,, \quad (2)$$

provided that its value at $z = 0$ is taken as the reference pressure level. For convenience pressures are expressed in lb/ft h^2. To obtain values in inches of water, multiply values in lb/ft h^2 by 4.61×10^{-10}.

If $\chi = 0$, Eq. (1) obviously describes the pressure of the outside atmosphere. With $\chi = 1$, the variation of the pressure in the shafts, p_S, is obtained. The values of χ for the other three types of building spaces namely χ_R (for rooms), χ_C (for corridors), and χ_U (for uncompartmented spaces) can be calculated if the three equivalent orifice areas, α_w, α_c, and α_s are known. In general, however, it is sufficiently accurate to use the following values: $\chi_R = 0.8$, $\chi_C = \chi_U = 0.9$.

Since α_w is usually much smaller than either α_c or α_s, it is permissible (as well as convenient) to assume that the only resistance to the movement of air is that offered by the outside walls of the building. With this assumption, the total rate of air infiltration can be calculated as follows (McGuire and Tamura 1975):

$$V_a = (\beta \alpha_w PB)(3T_a)^{-1} \cdot [g(1 - T_a/T_i)]^{1/2} H^{3/2}. \qquad (3)$$

Surveys of the leakage characteristics of exterior walls of tall buildings (Tamura and Wilson 1967; Tamura and Shaw 1976) indicate that, for lack of more accurate information, $\alpha_w \approx 0.0005$ ft^2/ft^2 is a reasonably conservative selection.

If fire breaks out below midheight of the building, the air currents rising in the shafts carry the smoke and distribute it to the compartments on the upper levels. Figure 2c shows the pattern of smoke distribution in the nine-storey building 10 to 15 min after the outbreak of fire on the first floor. (The smoke contamination of the storey above the fire floor is caused by vertical leakage currents mentioned earlier.)

The most obvious step the building designer can take to alleviate the smoke problem is to avoid specifying lining materials that are known to be heavy smoke producers or that generate highly toxic decomposition and combustion products. Yet, this "passive" method of defence is rarely sufficient. From among the "active" methods three will be discussed here briefly: smoke dilution, provision of refuge areas, and building pressurization.

In milder climates, where the role of stack effect in smoke dispersion may not be significant, the technique of diluting the smoke is often used in keeping certain vital parts of the building, such as lobbies and stairwells, relatively free of smoke. It is believed (McGuire et al. 1970) that dilution with fresh air in a 100 to 1 proportion will ensure safe conditions with respect to both visibility and toxicity. The information needed for the design of smoke dilution systems includes the equivalent orifice area for the boundaries of the space to be kept smoke-free and the rate of smoke generation by the fire. (The latter can be estimated as described by Harmathy 1972.)

Detailed studies have revealed (Galbreath 1969; Pauls 1975) that the time for evacuating a building in case of fire is approximately proportional to the building height and, depending on the occupant concentration, may take much longer than the expected duration of an average fire. Consequently, complete evacuation of a building above a certain height, say 10 to 15 storeys, does not seem practicable. The danger of exposing the occupants to smoke can be greatly reduced by providing pressurized refuge areas, preferably in the vicinity of a stairwell, where the occupants can stay in relative safety for the duration of the fire. The required rate of air supply to these areas is not likely to be determined by the leakage characteristics of its boundaries, but rather by the need for maintaining tolerable conditions for the assembled occupants. The required minimum flow rate of fresh air is 15 ft^3/min per person (ASHRAE 62-73).

The most effective way of preventing the spread of smoke is to pressurize the entire building or some major parts of it. Smoke travel through the shafts to the upper storeys of the building is eliminated if the pressure everywhere in the building, or at least in the vertical shafts, is raised above that of the outside atmosphere. This can be accomplished by supplying air to the interior at a rate sufficient to shift the pressure distribution in the shafts (see line A–A in Fig. 2b) to a new position (line O–A′) which is characterized by the equality of the internal and external pressures at the ground floor level (at $z = 0$). The required rate of air supply is (McGuire and Tamura 1975).

$$W_a = 2^{3/2} V_a, \qquad (4)$$

i.e., roughly three times the rate of infiltration of air into the building under normal conditions. As Fig. 2b shows, the pressure difference, Δp, against which the supply fan has to work, is equal to the difference between the pressure of the outside atmosphere and shaft pressure on the ground floor level. Thus, from Eq. (1) with $z = 0$.

$$\begin{aligned}\Delta p &= (p_a - p_S)_o \\ &= gB(1/T_a - 1/T_i)H/2\,. \end{aligned} \qquad (5)$$

There are two ways of achieving building pressurization. The more popular method is converting the air-handling system of the building to emergency operation and venting the fire floor (Tamura et al. 1970). The conversion entails the shutdown of the return and exhaust fans of the system, together with their associated branch and outside dampers. This method, however, has some pitfalls (Tamura and McGuire, 1973).

Pressurization can be more conveniently achieved by injecting outside air into all shafts at the top of the building. Additional advantages (and savings in energy consumption can be gained by preheating the air to only slightly above the 32 F level (provided that the outside temperature is below the freezing point). As the cool air lowers the temperature in the shafts and parts of the building, the pressure in the building further increases (see A′–A″ in Fig. 2b) and the flushing out of smoke from the building is accelerated.

The discussion of smoke control techniques has been restricted here to the simplest high-rise buildings, those with uniform compartmentation and with shafts that run the full height of the building. In more complex situations the design is rarely possible without a computer-aided analysis (Barrett and Locklin 1968; Tamura 1969; Wakamatsu 1976). Moreover, even for simpler buildings, invoking the computer may be necessary if building pressurization is combined with other techniques (Tamura 1970; Fung and Zile 1975).

A supplement to the National Building Code of Canada (Assoc. Comm. on Nat. Build. Code 1973) contains an exhaustive survey of measures for providing fire safety in high buildings. Some of them are just common-sense solutions and impose very little restriction on the design.

THE FULLY DEVELOPED FIRE

The curve shown in Fig. 3 is typical of the temperature history of a fire confined to a single compartment and unattended by fire fighters. During the growth period of the fire the temperature of the compartment gases is grossly nonuniform (see Fig. 1) and the average temperature increases slowly. At flashover the windows break and the period of "fully developed fire" sets in. It is characterized by much higher temperatures and improved uniformity in the spatial distribution of temperature. The temperature becomes nonuniform again and drops steadily as the fire enters its third period, the "decay" period, during which the flames die out and the charring remains of the fuel oxidize.

Because professional help by fire-fighters must not be taken for granted, the building designer has to accept responsibility for using the best available knowledge and techniques to ensure that a fire, no matter where it may break out, will remain localized and relatively benign. As roughly 70% of the fuel energy is released during its fully developed period, the characteristics of fire during this period are obviously of utmost importance in planning a defence.

It is traditionally held that a building subdivided by fire-resistant elements into reasonably sized compartments provides the best assurance against destructive fires. While there is little quarrel about the merits of fire-resistant compartmentation, the method of deciding on the required fire resistance of the dividing elements and the way of determining it have come under increasing criticism.

The standard fire resistance test (ASTM E 119-76) is still the most widely accepted way of evaluating the fire-resistant quality of building elements. Unfortunately this test suffers from the same defect as most other fire tests standards, namely that for the sake of ensuring commensurability of the test results on a unique quality scale, the test conditions are idealized to an unjustifiable extent. By scrutinizing the way the standard tests are conducted and the test results evaluated, one will find that the philosophy

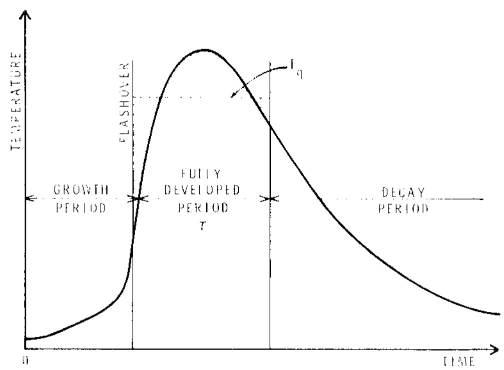

FIG. 3. Temperature history of a typical fire.

of fire resistance testing is based on the following four assumptions:

1) the severity of fire in a compartment is uniquely determined by the fire load;
2) the fire always develops in a definite manner characterized by a unique temperature-time curve;
3) the spread of fire is due to thermal or structural failure of an element (wall, floor, or ceiling) of the compartment boundary; and, therefore,
4) structural failure because of exposure of a boundary element from two sides is not possible.

Whereas the fallacy of the first two assumptions is clearly recognized now, and they are gradually being eliminated from modern practices of fire resistance evaluation (Pettersson et al. 1976), the inadequacy of the third and fourth assumptions is still not fully realized.

Even though building elements may occasionally fail in ways assumed by the philosophy of fire resistance testing, namely by conduction of heat through, or collapse of, one or more boundaries of the compartment on fire (see Fig. 4a), in the vast majority of cases the spread of flaming combustion is a convective-radiant process. The flames are driven by pressure differences from one compartment to another, either horizontally, mainly through doors left open by the escaping occupants, or vertically through poorly fire-stopped openings and by flames issuing from windows and then jumping to the storey above (Fig. 4b). Consequently, the fact alone that a building is well compartmented and the compartment boundaries are fire resistant (in the conventional sense) is no assurance against fire spread.

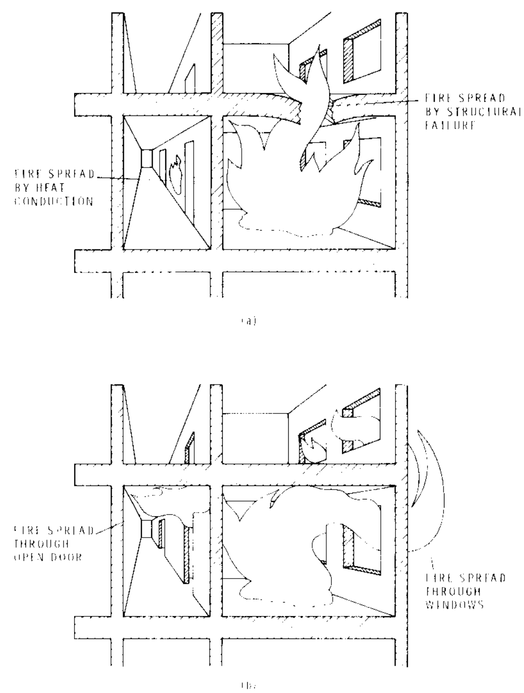

FIG. 4. Mechanisms of fire spread (a) Mechanisms implied by the philosophy of fire testing (b) Actual mechanisms.

Once the fire has spread (horizontally or vertically) to a neighbouring compartment, the building element, wall or floor, that forms the common boundary of the two compartments becomes exposed to fire on both sides, a condition not considered in the standard test practices. Consequently, an element judged from a standard fire test as sufficiently fire resistant may collapse in a real-world (spreading) fire.

Because, as discussed, the lack of provision for two-sided fire exposure is only one of several weaknesses in the standard fire resistance test procedure, the current practice of providing safety is somewhat illusory. Fortunately, the characteristics of fully developed (postflashover) fires are fairly well understood by now, and it is possible to devise truly effective measures against destructive fires.

From an analysis of the results of hundreds of compartment burnout tests (Kawagoe, 1958; Gross and Robertson 1965; Butcher et al. 1966, 1967) and some earlier theoretical studies (Kawagoe 1967, Thomas et al. 1967; Magnusson and Thelandersson 1970), the following three parameters have been introduced to characterize the "severity" (destructive potential) of fully developed fires (Harmathy 1972): its duration, τ (see Fig. 3); the average temperature of the compartment gases, T_g; and the "effective heat flux," q_E, i.e., the average heat flux that penetrates the compartment boundaries. All three depend primarily on two variables, the total "fire load" (the amount of combustibles in the compartment), G, and the rate of entry of air into the compartment (ventilation) U_a. T_g and q_E also depend, to a lesser degree, on the size of the compartment and the thermal properties of the lining materials.

If the doors remain closed and air enters only through the broken windows of the compartment,

$$U_a = 230 A_W \sqrt{h_W} . \qquad (6)$$

As long as the fire load consists predominantly (in 85 to 90%) cellulosic materials in the form of ordinary furnishing items, the ratio U_a/G determines the main characteristics of the fire. If U_a/G is less than a critical value, $(U_a/G)_{cr}$ (equal to about 18.2 h^{-1}), the rate of burning is roughly proportional to U_a, and the fire is referred to as "ventilation-controlled." If, on the hand, $U_a/G \geqslant (U_a/G)_{cr}$, the rate of burning is proportional to G; the fire is "fuel-surface-controlled."

The duration of fully developed fire can be calculated from the following equations (Harmathy 1972):

for ventilation-controlled conditions

$$\text{if} \quad U_a/G < 18.2 , \quad \tau = 5.72 G/U_a ; \qquad (7)$$

for fuel-surface-controlled conditions

$$\text{if} \quad U_a/G \geqslant 18.2 , \quad \tau = 0.314 . \qquad (8)$$

It is important to note from Eq. (8) that for fuel-surface-controlled conditions, the duration of fully developed fire (for conventional furnishing) is very short, about 19 min (0.314 h), and independent of the fire load and ventilation.

Unfortunately, the calculation of the two fire severity parameters, T_g and q_E, is somewhat more complicated. It involves the simultaneous solution of two equations [Eqs. (51) and (62) in Harmathy 1972].

Figure 5 shows the variation of the duration of fully developed fire, τ, with the "air flow factor," defined as $(U_a/G)/(U_a/G)_{cr}$, as calculated from Eqs. (7) and (8). It also depicts the dependence of the temperature, T_g, on the air flow factor, at three values of the "specific fire load," G/A_F (where A_F is the floor area of the compartment). In Fig. 6 the variation of the effective heat flux, q_E, is plotted against the air flow factor for the same three values of the specific fire load. Although the curves of T_g and q_E relate to a particular set of conditions (described in Butcher et al. 1966, 1967), they can be regarded as typical. Attention is called to the fact that the highest temperatures usually occur at relatively low air flow rates (in other words, under ventilation-controlled conditions), whereas the maxima of the effective heat flux always coincide with $(U_a/G)_{cr}$.

The designer, guided by statistical data on specific fire load in various occupancies (Witteveen 1966; Baldwin et al. 1970; Nilsson 1970; Berggren and Erikson 1970; Cerberus Alarm 1971; Bryl 1975; Culver 1976) and by the preceding discussion, can make a fair estimate of the fire severity parameters for all compartments of the building under design. Once this information is available, he can proceed with specifying for each building element the requirements that will ensure its satisfactory performance in case of fire.

A clear distinction must be made between "key structural elements" and "dividing elements." Key elements are those, the

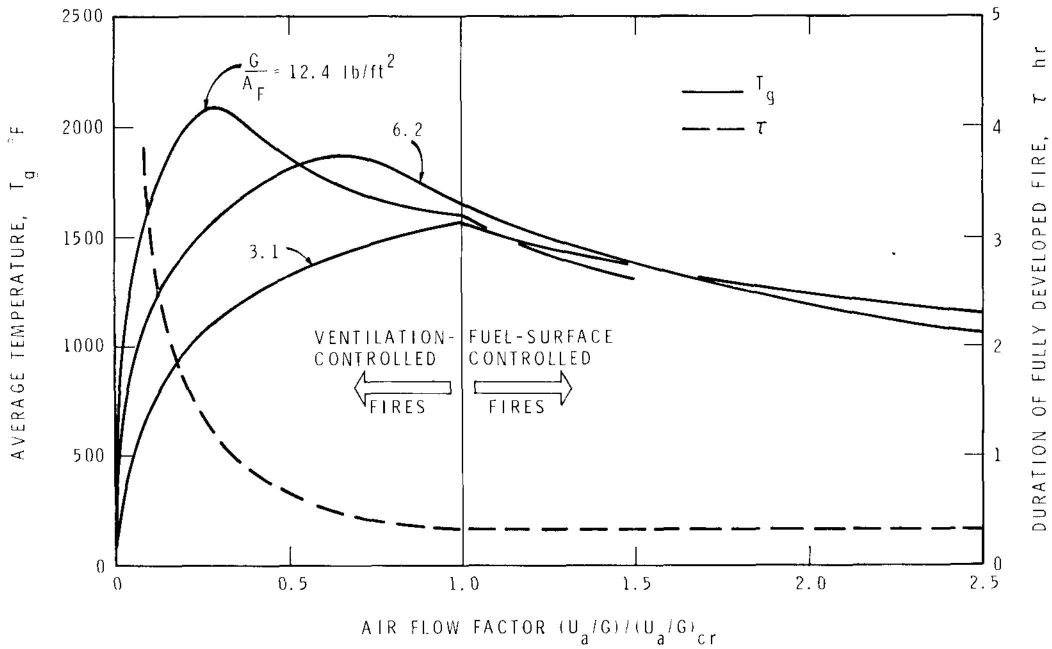

FIG. 5. Duration of fully developed fire and average fire temperature (the latter for a specific set of conditions).

collapse or major deformation of which may endanger the stability of the building. It is advisable that the appropriate fire protection of each of these key elements be evaluated from comprehensive heat flow studies, similar to those outlined in Harmathy (1976a, 1977). If there is a possibility, however remote, that the element may become exposed to fire on both sides, two values of the effective heat flux, q_E, and of the period of fully developed fire, τ (one for the compartment under study and one for the adjacent compartment), will form the basic input information. All realistic possibilities of simultaneous and delayed exposure of the two sides to fire should be examined. Studies of this kind indicated that simultaneous exposure of the two sides does not necessarily represent the most adverse conditions; increasingly delayed exposure of the reverse side may create increasingly detrimental conditions.

Such scrupulous studies are not justified, however, in the case of simple dividing elements that are not parts of the load-bearing network. Because, once the fire has spread to its reverse side, a dividing element has no further role in the provision of fire safety, there is no need for requiring it to withstand fire from both sides. In fact, if U_a/G for both adjacent compartments is higher than the critical value, 18.2 h^{-1}, specifying a 30-min fire resistance (as evaluated from standard fire resistance test) is adequate. This claim is based on the finding that for fuel-surface-controlled fires the duration of fully-developed fire is only about 19 min [see Eq. (8)].

Figure 5 shows that not only are fuel-surface-controlled fires, short, but they develop at relatively low temperatures. The designer may, therefore, consciously aim at providing conditions that would favour fuel-surface-controlled fires. In other words, the designer has a certain degree of freedom in designing the fire itself, as well as the protection against it.

Fuel-surface-controlled conditions are expected to prevail if relatively large windows are selected, such that

$$A_W \geqslant 0.079\, G/\sqrt{h_W}\,. \tag{9}$$

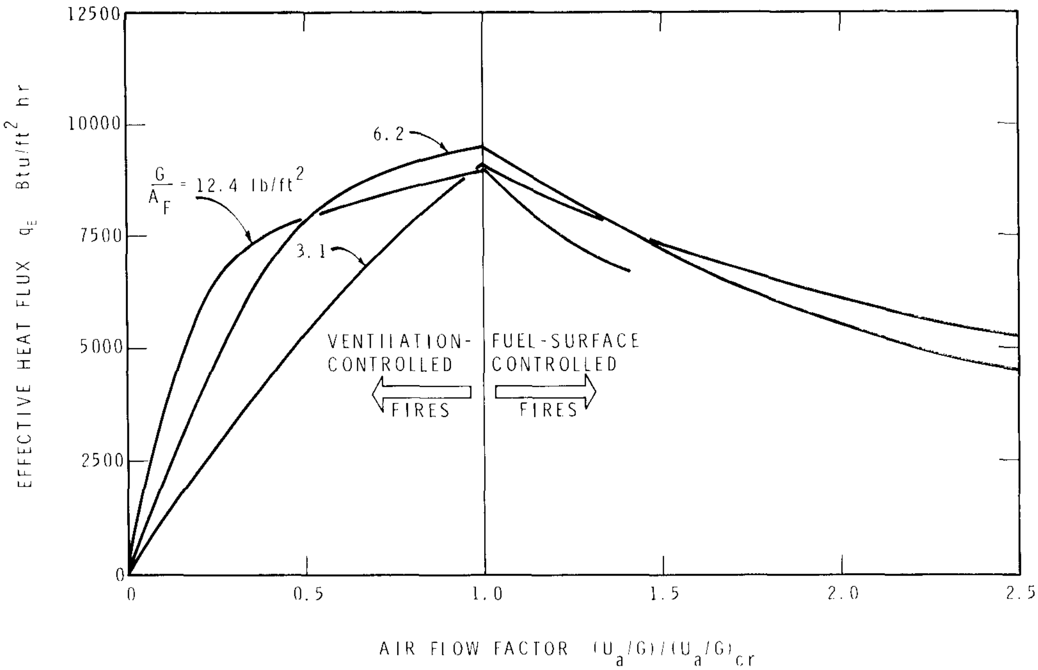

FIG. 6. Effective heat flux (for a specific set of conditions).

[This relationship has been obtained by expressing $(U_a/G)_{cr}$ in terms of window area with the aid of Eq. (6)].

Although the possibility of fire spread must never be ruled out in the design for fire safety, the designer is well advised to use all available techniques to *minimize* the probability of spread. The simplest and most effective way of achieving this is specifying self-closing compartment doors. Several building codes have already made the use of self-closing doors mandatory in high-rise buildings. Unfortunately, hinged doors may present some problems if fire breaks out in one of the lower storeys during the winter heating season. After the windows of the fire cell are broken, it may be difficult or even impossible to open the corridor door because of the large pressure differences between its two sides. It would be more practical to use weight-operated sliding doors of some light construction. If such doors are hung by rollers from a concealed rail and supported by two more rollers near the bottom, as shown in Fig. 7, opening them at any pressure difference would require less force than that required to open a hinged door equipped with a closing device at no pressure difference. Other solutions that offer similar advantages are also available (Williamson 1976).

A door that remains closed during the fire is an effective barrier not only against the spread of fire but also against the spread of smoke. A numerical example worked out for a 20-storey building, with the fire occurring in the winter in one of the first-storey compartments, indicated that the rate of smoke spread is reduced by a factor of at least 30 by closing the door of the fire cell. Further reduction can be achieved by the application of a special material (Badische Anilin) along the edges that would expand on heating to fill gaps around the door.

Vertical or horizontal spread of fire can often be traced back to the penetration of the floors or walls by plastic DWV (drain, waste, and vent) pipes and telephone or electric cables. Fire tests indicate (Mc-

Guire 1973, 1975; Orals and Quigg 1976) that it is sound practice to surround these pipes and cables with a noncombustible packing housed in a thin sheet steel sleeve extending beyond the surface of the floor or wall.

A systematic investigation conducted in Australia (Com. Exp. Build. Stn. 1971) confirmed the earlier British finding that 2-ft projections over the windows of a building do not prevent flames issuing through windows from curling back and igniting the storey above. It was found, however, that projections wider than 3–4 ft are effective in keeping the flames away from the face of the building and in reducing radiation to the storey above to an acceptable level.

Continuous balconies and open corridors can play a useful part in protecting buildings against the vertical spread of fires. Unfortunately, their use is rarely considered nowadays even for residential buildings, because they cut down the natural daylight reaching the interior, increase the building costs, and may produce aesthetically undesirable effects.

Simple "flame detectors" (Harmathy 1976b) can provide the same degree of protection as continuous balconies and open corridors, at substantially lower cost and without the aforementioned drawbacks. They are light metal panels mounted above each window and held in vertical position by a fusible part, possibly a nut. The width of these panels is at least 3 ft 3 inches and their length equal to the window breadth plus about 4 ft. As Fig. 8 shows, the deflector falls down to assume horizontal position when activated by flames issuing from the window below. Covered with baked-on enamel, or furnished with bronzed, imprinted surfaces, for example, the deflectors may be consciously applied to the building as decorative elements.

A high degree of fire safety can be achieved by a new technique referred to as "fire drainage" (Harmathy 1976b). It utilizes the energy of fire in three ways: (1) by drawing air into the fire cell in quantities that ensure fuel-surface-controlled

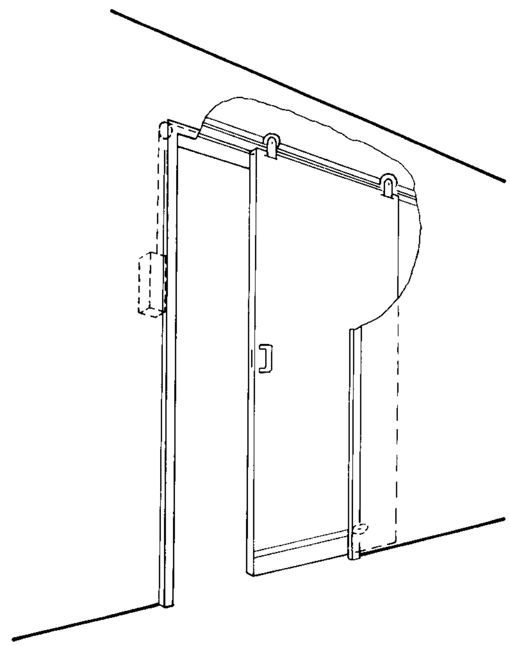

Fig. 7. Self-closing sliding door.

conditions, i.e., short fire duration and relatively low fire temperature; (2) by keeping the pressure in the fire cell below the pressure levels prevailing in the neighbouring spaces; and (3) by removing the smoke and flames from the fire cell in a safe and organized manner.

Figure 9 shows a large, uncompartmented space equipped with a fire drainage system. The ceiling is divided into many rectangular areas by a series of retracted fold-up drop curtains, 1, made of light-gauge metal and equipped with weightier bottom pieces. The purpose of these curtains is twofold: they restrict the spread of flames and smoke during the growth period of fire; and when activated by the fire, they slide down in grooves, 2, to floor skirting boards, 3, and surround the cell on fire, 4, leaving only four openings, 5, properly sized for controlled ventilation.

There is a column, 6, in the center of each cell. A well-insulated "drainage duct," 7, runs the entire height of the building in the interior of the columns. Each duct has four "access gates," 8 (insulated on the duct

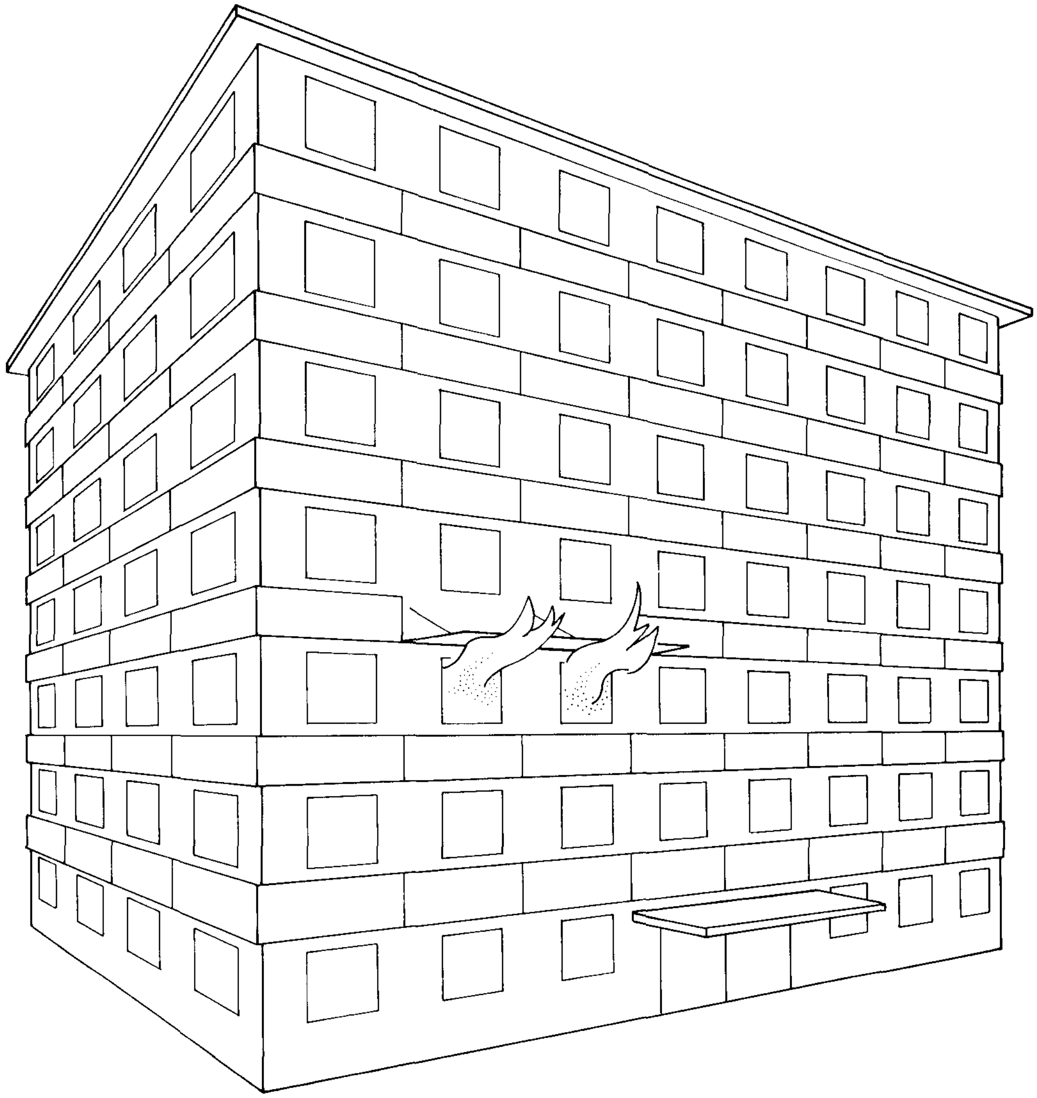

FIG. 8. Flame deflectors in operation.

side), near the ceiling on every storey, by which it serves a number of cells located on the successive storeys. These gates are normally closed by simple fusible parts. There are two or four "release gates" (not shown) at the top end of each drainage duct above the roof level. They are held closed by the tension of a heat-destructible line extending to the bottom of the duct.

As fire in the cell starts to build up, the access gates, 8, open shortly before the activation of the drop curtains, 1. The fire gases enter the drainage duct, 7, and, by destroying the tensioning line, cause the release gates at the top to open. Not only are the gases and flames safely withdrawn from the building, but the suction created by the column of hot combustion products in the duct creates a depression in the fire cell and thus prevents the dispersion of smoke and fire to the neighbouring spaces.

The design of the fire drainage system

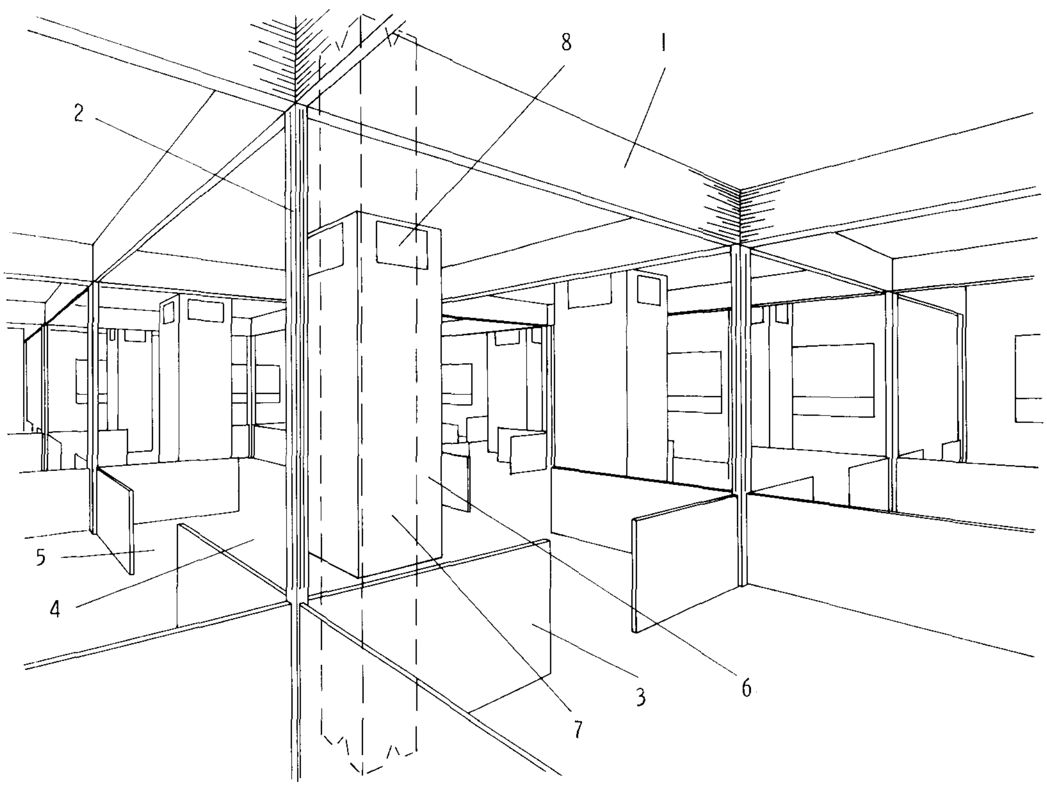

Fig. 9. Uncompartmented space equipped with fire drainage system.

involves the calculation of the cross-sectional area of the drainage duct and the area of entry of air into the cell (the sum of the four openings, 5, in the floor skirting boards). The procedure is described briefly by Harmathy (1976b).

Since operation of the fire drainage system does not rely on the availability of water and electricity at the time of fire (the charring remnants of the fuel can be extinguished with some chemical suppressant), its application may offer special advantages in remote, poorly serviced communities, or with buildings the contents of which are sensitive to water damage. The disadvantage of the system is that with its use the normal loss expectancy is an entire cell and, therefore, it is not suitable for the protection of buildings with valuable contents.

CONCLUSIONS

Although the most important aspects of the design of buildings for fire safety are governed by building codes, a competent design team is capable of greatly increasing the level of safety beyond that provided by the stereotyped application of regulations, usually without any additional expenditures, or even at substantial savings to the builder. It is extremely important to realize, however, that fire safety is not something that can be added on after completion of the building plans. To be really effective, the problem of fire safety must be taken into account from the first step of architectural design.

Discussion in this paper was confined to the more or less conventional types of buildings of residential, business, and institutional occupancies. With buildings erected for housing large crowds a variety of other fire safety problems will inevitably arise (Phillips, 1974), many of them not covered adequately by building codes. The inclusion of a fire safety expert in the design of such buildings is not just a wise move, it is essential.

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