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DESIGN APPROACH TO FIRE SAFETY IN BUILDINGS

BY

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Life safety

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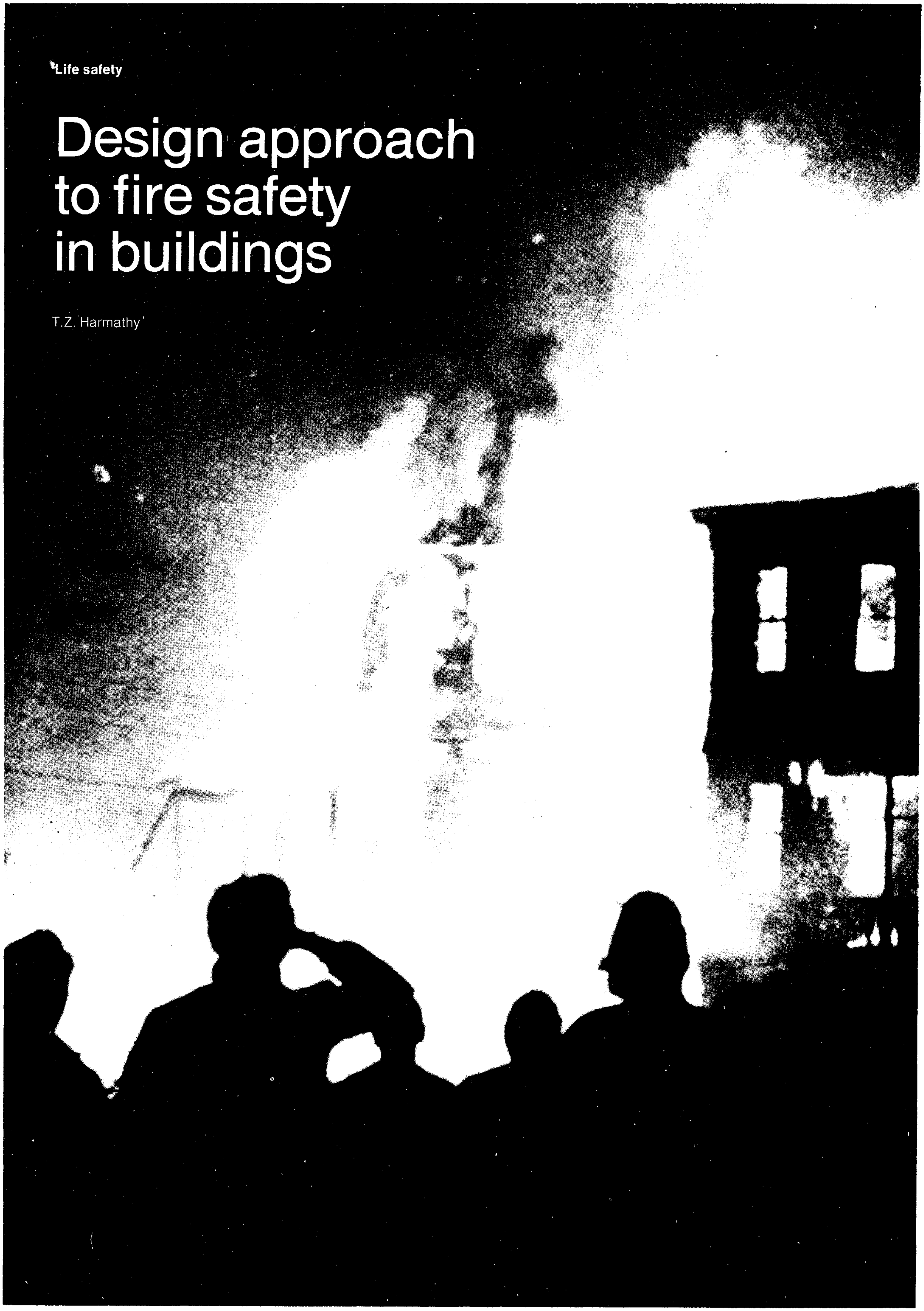

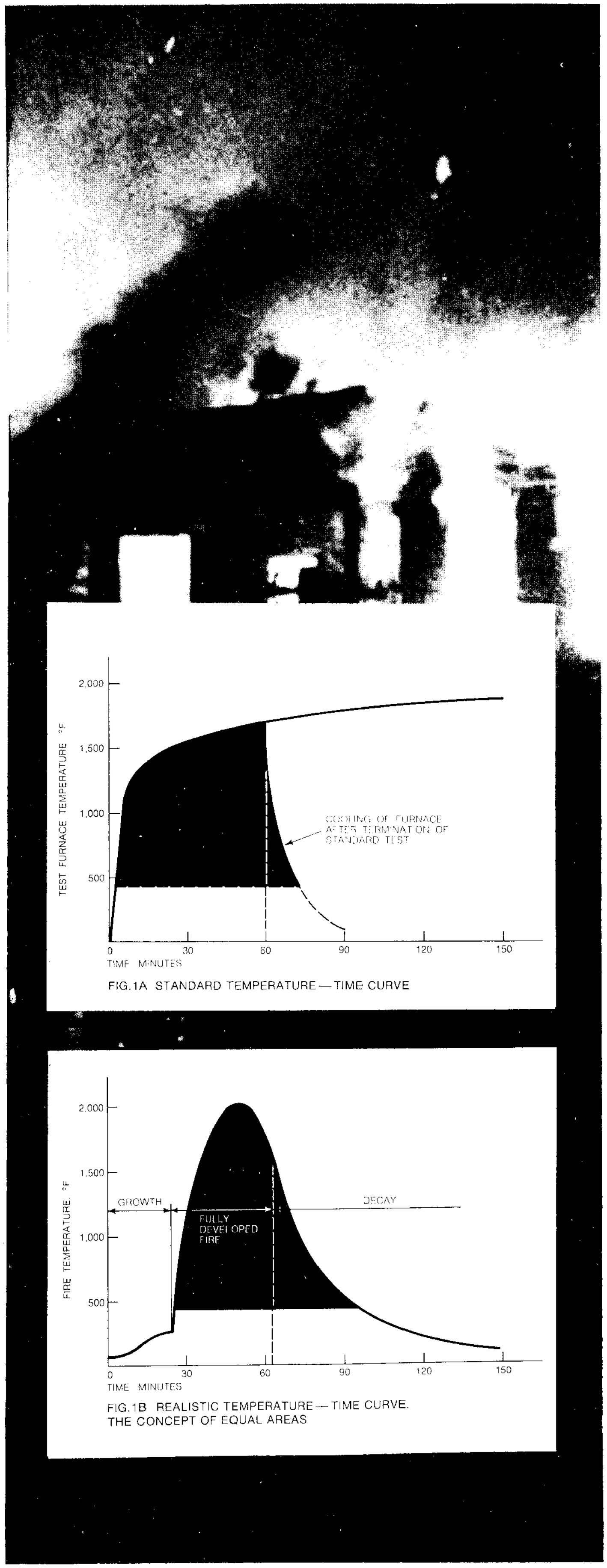

FIG.1A STANDARD TEMPERATURE—TIME CURVE

FIG.1B REALISTIC TEMPERATURE—TIME CURVE. THE CONCEPT OF EQUAL AREAS

Fire safety as provided for by present building codes is examined critically and the characteristics of building fires are reviewed. A new design approach is suggested.

In some respects, the process of designing a building for fire safety may be described as faithfully executing code regulations, since the most important aspects of providing fire safety in buildings are governed by strict codes. There are encouraging signs, however, that this situation will change during the coming years and the designer will be free to select the most effective means of coping with the fire problem.

Traditionally, building compartmentation provided functional units or offered occupants some degree of privacy. From the point of view of fire safety, however, compartmentation is regarded as the means for breaking up total building volume into small cells where, with an efficient protection system, fires can be localized and suppressed. To prevent fire from spreading from one compartment to another, various building codes require compartments be made structurally sound enough to withstand a more or less full fire exposure without major damage, and that boundaries be capable of acting as heat conduction barriers. During the past several decades, standard fire tests have been developed to determine whether the structural and boundary elements of the compartment (beams, walls, floor, etc.) fulfill these requirements. In North America ASTM Method E119 specifies the conduct of these tests and the interpretation of the findings.

In a fire test, a representative sample of the compartment element is exposed on one side (walls, floors, ceilings, beams) or on all sides (columns) to the heat of a test furnace. Test conditions are required to follow a temperature-time curve assumed originally to reproduce the temperature history of a fully developed compartment fire (fig. 1a). The length of the element's exposure to the test fire is the period for which "fire endurance rating" (expressed in hours, ¾, 1, 1½, 2 etc.) is desired. Required minimum ratings are specified by the various building codes for identified building types. (Penalties are imposed on buildings having excessively large floor areas or unusual heights.) If the specimen element withstands the simulated fire exposure for ¾, 1, 1½, etc. hours without major structural damage and substantial heat transmission (see ASTM E119-71 for the interpretation of these expressions), it is "rated" as a ¾-, 1-, 1½-hr etc. fire-resistant element. A compartment built entirely of elements with fire endurance ratings (fire ratings, for short) not less than the minimum specified by the building code for the type of building is referred to as a fire-resistant compartment. The essence of the "building code approach" is to rely entirely on the building code specifications to provide fire safety.

Fire load concept

Although the bases on which fire endurance ratings are assigned by the writers of building codes are, by now, not clearly recognizable, the underlying concept unquestionably rests on pioneer work by S.H. Ingberg[1] more than 40 years ago. Ingberg suggested that fire endurance requirements

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should be determined on the basis of potential "fire severity" (to be discussed later). He believed, further, that fire severity is uniquely related to "fire load" (weight of combustible materials per unit floor area) characteristic of the occupancy considered. The expected magnitude of the fire load may be judged from data collected in England a few years ago. The mean fire load in modern office buildings is 4.1 lb/sq ft and in 95 percent of rooms it is less than 12.0 lb/sq ft. (In storage rooms the fire load may be 25 lb/sq ft or higher.[3]) His suggestion was equivalent to advocating that fire endurance requirements be prescribed on the basis of characteristic fire loads.

Ingberg's experiments seemed to indicate that, with fire loads up to 30 lb/sq ft the fire endurance requirement is approximately 0.1 hr for every 1 lb/sq ft fire load. Thus, for a fire load of 7.5 lb/sq ft the required minimum fire endurance would be taken as ¾ hr, that for 20 lb/sq ft as 2 hr, etc. (Fractional fire endurance requirements are always rounded upward to the nearest ¼ hr in practice; for example, the requirement at a fire load of 12.4 lb/sq ft is 1½ hr rather than 1.24 hr.) The concept of the fire load as the only significant factor determining the severity of fire and, in turn, the fire endurance requirement, seems to be founded on two basic premises: 1) that all compartment fires burn at approximately the same rate; 2) that a definite portion of the combustion heat is always absorbed within the compartment by its elements.

The room shown in fig. 2 contained a great deal of combustible material, so that the fire will be very severe. If built according to building code regulations, the elements of the room must therefore have high fire endurance, that is, all load-bearing components must be protected by thick insulating covers. Research during the past 10 to 15 years has shown conclusively that the fire load concept, which still forms the basis of the "building code approach," is inaccurate and may result in both under-protected and grossly over-protected buildings.

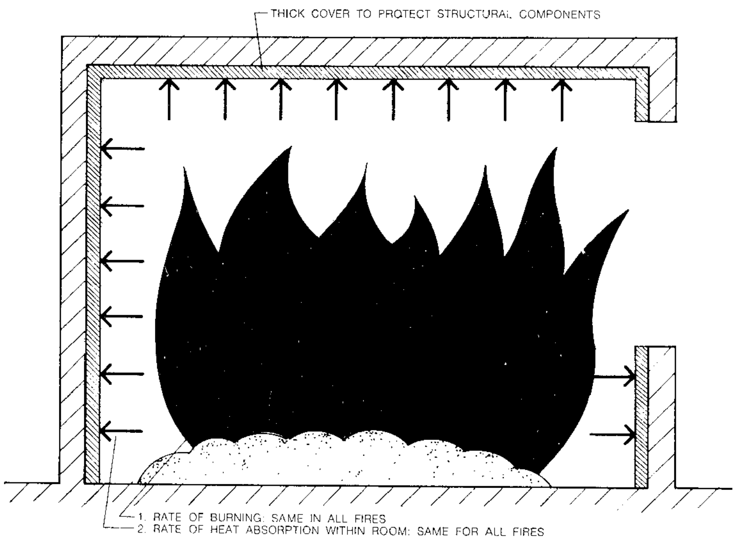

FIG. 2 CONVENTIONAL FIRE PROTECTION PHILOSOPHY

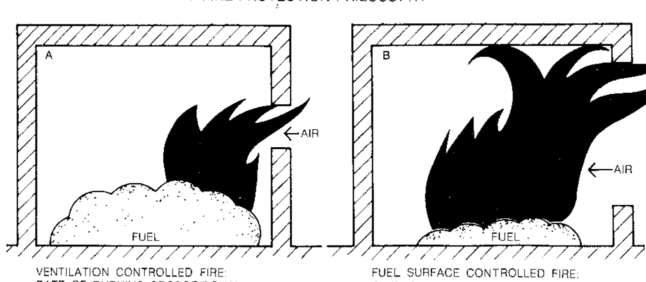

FIG. 3 TWO TYPES OF FIRE FROM THE POINT OF VIEW OF RATE OF BURNING

Characteristics of compartment fires

On the basis of research results from all over the world, the author has recently offered a more realistic picture of the process of compartment burning.[4] Fig. 1b shows a typical temperature-time curve for actual compartment fires that may be divided into three periods: growth, fully developed fire, and decay. The beginning of the period of fully developed fire is readily recognized by a sudden rise of temperature; its end is, by definition,[3] the point at which the fire temperature drops to 80 percent of its maximum value. As the bulk of the fuel (furnishing and other contents) burns away during this period it is the only period that deserves consideration from the point of view of structural fire damage. Contrary to earlier beliefs, the rate of burning in a compartment (during the fully developed period) may vary within very wide limits. Two major factors determine the rate of burning: fire load and ventilation, the latter usually expressed in terms of rate of fresh air flow into a compartment. With natural ventilation the air flow rate, U_a (lb/sec), can be calculated from the equation: $U_a = \frac{1}{15} A_W \sqrt{h}$ where A_W is the total area of windows, in sq ft, and h is the height of windows, in ft.

This equation has been derived on the assumption that all window panes break and fall out at the beginning of the fully developed fire period. Sometimes, especially with double-glazed windows, breakage remains incomplete and the actual air flow may be less, by 30 to 50 percent, than the calculated value. On the other hand, the flow of outside air through the window can be increased or decreased by pressure differences due to building stack effect, depending upon building height and outside temperature. With forced ventilation, the rate of air flow is interpreted as that produced by mechanical means (provided that failure of the mechanical device during the fire is unlikely).

Depending on the relative magnitude of the fire load and on ventilation, two types of conditions may exist in a burning compartment (fig. 3).[4] 1) If the fire load is high and ventilation poor (fig. 3a), the amount of combustible material burning at any one time is controlled by the rate of air flow. As ventilation (window area) increases, combustion extends to larger and larger parts of the fuel and the rate of burning increases. The fire is "ventilation controlled." 2) If the fire load is relatively small and ventilation good (fig. 3b), air entering the room is more than enough to keep all combustible materials burning simultaneously. The rate of burning is controlled by the surface area of the fuel; the fire is "fuel surface controlled."

The fire load concept implies that the same proportion of heat of combustion is always absorbed within a compartment. In reality, two conditions may exist (fig. 4): 1) If the rate of burning is low and the room has a high ceiling (fig. 4a), the combustion process will develop entirely within the compartment and a large portion of the heat of combustion will be absorbed by the various structural and boundary elements of the compartment. 2) If, however, the rate of burning is high and the room has a low ceiling (fig. 4b), flames will issue from the windows and a considerable portion of the fuel energy, sometimes 50 percent or more, will be released outside. Thus the heat flux (amount of heat [in Btus] that passes through a unit area [sq ft] in unit time [hr]) available for the destruction of the structural components of the room becomes less intense.

Concept of equal areas

An essential part of Ingberg's concept[1] was a specific way of defining "fire severity" (destructive potential). Although his second fundamental idea, the assumption of a unique relationship between fire severity and fire load, is not appreciated today, his definition of fire severity (sometimes in slightly modified forms) is still widely used among research workers. Ingberg defined fire severity as the area under the curve of fire temperature (above some reference level, usually 301 or 572F) versus time, for actual compartment fires or standard test fires. This definition implies that long, relatively cool fires and short, intense fires are similar with respect to destructive potential and, therefore, that the requirements for fire endurance of compartment elements should also be similar.

The most attractive feature of this definition is that it is a convenient way of assigning supposedly more realistic fire endurance requirements to elements of any compartment whose expected fire temperature history can be predicted (from experiments) or can be estimated (by heat balance calculations).[3,5,6] This concept of establishing fire endurance requirements may be referred to as the "concept of equal areas." In the illustration of this concept (fig. 1) 437F was selected as the reference level for the calculation of areas (the average of the two values suggested by Ingberg). It may be seen that a 1-hr exposure to a standard fire test will match the severity of the compartment fire shown (fig. 1b) and, therefore, that the elements of this compartment should be of at least 1-hr fire endurance. Because the fire temperature versus time curve faithfully reflects ventilation effects, compartment dimensions, and properties of lining materials (in addition to that of the fire load), replacing the fire load concept by the concept of equal areas in determining fire endurance requirements is undoubtedly a step forward.

Fire severity parameters

Unfortunately, the concept of characterizing fire severity by some area under the fire temperature versus time curve cannot be strictly justified on scientific grounds. In general, temperature plays a more important part in the structural failure of compartment elements than does fire duration. It might be thought that the average temperature of the fire alone would be a better indication of fire severity, but this view also would be incorrect. For example, the temperature climbs higher in a compartment lined with good insulating materials than in one that is not, but the fire damage is lighter; in other words, the fire appears to be less severe.

According to recent studies,[3] there are at least three independent parameters whose values have substantial bearing on expected fire damage (fig. 5): 1) duration of fully developed fire (τ in hrs or min), 2) average fire temperature: average temperature of the gases in the compartment during the fully developed period of fire, T_g (in °F), and 3) "effective" heat flux: average heat flux available for penetration of the elements of the compartment during the fully developed period of fire, $\bar{q}_E$ (in Btu/sq ft hr).

It is no surprise that these parameters depend primarily on fire load and ventilation. Fig. 6 shows the variation of fire duration and average fire temperature with increasing ventilation (increasing window areas) for three different fire loads: 12.4, 6.2 and 3.1 lb/sq ft. This information is related to a room 25′ x 12′ in area, 9′ -5″ high and lined with concrete and vermiculite plaster.[7,8] Arrows indicate the critical air flow at which, with increasing ventilation, the fire ceases to be ventilation controlled and becomes controlled by the surface area of fuel (combustible contents of the room). (Critical air flow can be calculated from the equations presented in Ref. 3. One can assume, as a rough guide, that with natural ventilation fuel-surface-controlled conditions will prevail if the ratio of the total fire load [in lb] to the total window area [in sq ft] is less than about 30 lb/sq ft. See also Ref. 2 and 9.)

As expected, the fire temperature is always higher for higher fire loads. Starting with zero air flow, the fire temperature increases sharply with increasing ventilation (or window area). On reaching a maximum, generally still within the ventilation-controlled regime, it begins to decline owing to the fact that an increasingly larger portion of the burning will occur

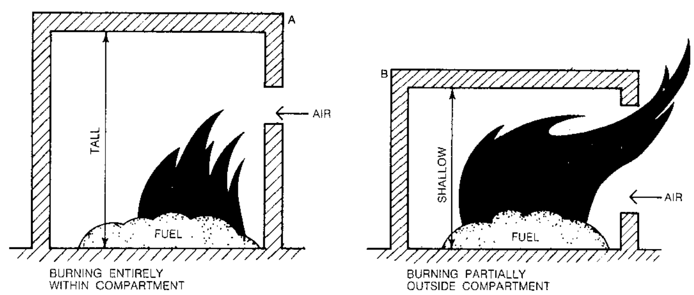

FIG. 4 TWO TYPES OF FIRE FROM THE POINT OF VIEW OF HEAT EVOLUTION WITHIN COMPARTMENT

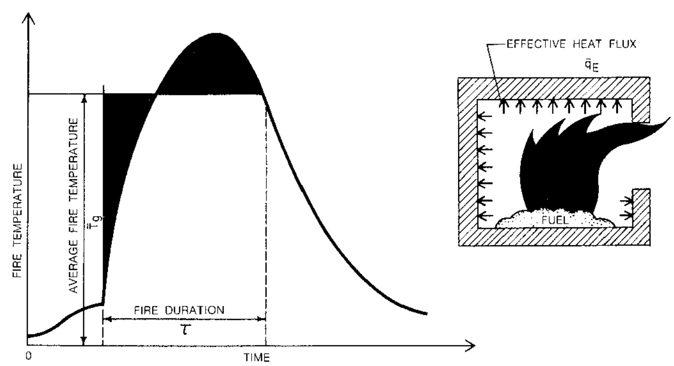

FIG. 5 ILLUSTRATION OF THE MEANING OF THE THREE FIRE SEVERITY PARAMETERS

outside the windows. As the air flow rate increases beyond the critical value, the temperature decreases steadily, because the rate of heat evolution is no longer affected by ventilation. The increasing inflow of cool air produces increasingly lower temperatures. As shown by thin dashed lines (fig. 6), any air flow over 15 lb/sec will keep the average fire temperature below 1000 F (generally accepted as the temperature level detrimental for steel) provided the fire load is not higher than 3 lb/sq ft. It is clear, therefore, that at lower fire loads even unprotected steel can be used safely if window areas are properly sized.

It may be seen that in the ventilation-controlled regime, the duration of the fully developed period of fire depends strongly on fire load and decreases sharply with increasing ventilation. In the fuel-surface-controlled regime, fire duration is very short, typically 20 min, and is independent of fire load. If, however, the fire load is high, it may not be possible to choose sufficiently large window areas to ensure that fuel-surface-controlled conditions prevail with natural ventilation.

Fig. 7 shows the variation of the third fire severity parameter, effective heat flux, with increasing ventilation. Again, the critical air flows are indicated by arrows. From the point of view of intensity of heat penetration into the boundary elements of the compartment, the borderline between ventilation- and fuel-surface-controlled fires seems to represent the most adverse condition.

Engineering design of fire protection

At which stage of design can knowledge about compartment fires be best put to use? In present practice, the provision of fire safety consists of little more than incorporating in the design some building code requirements. The responsibility for this is usually shared by the architect and engineer. There is a trend, however, to give the engineer greater responsibility, at least with respect to the structural fire safety of the building. Many believe that the problem of fire protection of structures should be handled by specially trained engineers. As visualized, the design of building elements for fire resistance by these engineers may consist of three principal stages: 1) calculation of the fire severity parameters for all compartments of the building from information concerning compartment dimensions, lining materials, ventilation, and fire load; (This information can be deduced from the building plans and from statistical data concerning the fire load in various occupancies.) 2) heat flow and stress-strain studies, using the fire severity parameters as input data; 3) decisions concerning the appropriate fire protection.

The advantage of this kind of engineering approach is clear. The engineer is not bound by any preconceived concepts, code regulations, or stereotyped testing requirement and can select the fire protection most suitable under the prevailing circumstances. It is worth noting that the engineering design of fire protection of load-supporting steel components is already an accepted practice in Sweden.[10] The main weakness of the approach is that the engineer commences his study toward the end of the overall design process. The available knowledge of the nature of potential fires could be used more effectively if it were considered from the beginning, during the architectural design. By changing some of the variables under his control, while satisfying the basic practical and aesthetic requirements, the building designer (architect) could drastically reduce the potential severity of building fires and thus could help the engineer save on (or completely dispense with) the costs of fire protection. This is why the author feels that this paper should be addressed to architects rather than to engineers.

Defensive and offensive design approaches

As has been pointed out,[4] the building designer can predetermine the nature of possible fires by proper selection of certain dimensions of the compartment, ventilation, and lining materials. This suggests a new, preventive approach to fire safety, based on decisions made at the architectural stage of the building design. The most important aspect of this approach is as follows: If calculations indicate that window areas can be large enough to ensure fuel-surface-controlled conditions in case of fire, and if such a selection is not objectionable from other points of view, *the designer can ensure that any fire will not last longer than 30 min.* Because, with certain restrictions, any noncombustible building element is capable of yielding at least 30-min fire endurance, it seems logical (as an introductory step) to allow the building designer the freedom to choose certain ventilation requirements insead of fire endurance. This deliberate use of dimensioning to improve fire safety can be called a "defensive" approach. It recognizes that although the building designer cannot prevent the occurrence of fires, he can ensure that fire will not spread to other compartments due to structural failure. He makes certain that any fire will be of short duration and of relatively low temperature, even at the expense of giving up entirely the contents of the fire compartment.

It is clear that this philosophy will not be practical if the contents of a building are of any appreciable value. In such cases an "offensive" design approach is appropriate, characterized by the use of special devices and facilities to detect fire and suppress it at an early stage. Numerous other situations may also rule out the use of the defensive approach. It may interfere with some fundamental requirement concerning the use of the building or it may result in increased energy consumption in certain climates. The defensive design approach to fire safety is only one of many design components the designer can use in producing functional, economical, attractive, and safe buildings.

Correct compartment design

Although the graphs presented in fig. 6 and 7 relate to a specific set of conditions, it is possible to generalize to some extent, to derive "rules" for the correct compartment design. It cannot be emphasized too strongly, however, that these rules are valid only from the point of view of structural fire protection. They may well be overruled by other considerations. The basic rule for designing compartments for minimum structural damage in fire is as follows: provide sufficient ventilation (natural or forced) to ensure that any fire will be fuel-surface-controlled. In this way it will be of short duration and the fire temperature will not rise excessively high.

If unprotected steel is to be used, check (by calculations described in Ref. 3) whether it is possible to provide sufficiently high ventilation to reduce the average fire temperature well below the critical 1000F limit. It is entirely probable that this cannot be done if the fire load is higher than 4 to 5 lb/sq ft. If unprotected steel is used in a compartment, do not use good insulating linings on other components of the compartment. Such linings are bound to raise the fire temperature and thus adversely affect the performance of the load-bearing steel components.

Finally, low ceilings are an effective means of forcing fire to burn outside the compartment. Recognition of this rule may be especially important in storage building design. Naturally, consideration must be given to the possibility of increased danger to the surroundings of the building, and to the danger of flames jumping from floor to floor along the façade.

Summary

It has been pointed out that stereotyped measures for fire safety specified by various building codes are inadequate in that they can result in both under-protected and over-protected buildings. With a better understanding of the characteristic features of compartment fires, the building designer will be in a better position to predetermine the nature of fire and to select the most appropriate way of dealing with it. He can either design compartments for minimum structural damage without the installation of special equipment (defensive approach), or he can provide special equipment for detecting and suppressing the fire (offensive approach). Although the best ways of improving fire safety in buildings depend on the particular circumstances, there are general rules that may help the building designer in his deliberations. It is hoped further work will shed more light on this area, especially on the relative merits of defensive and offensive design approaches.

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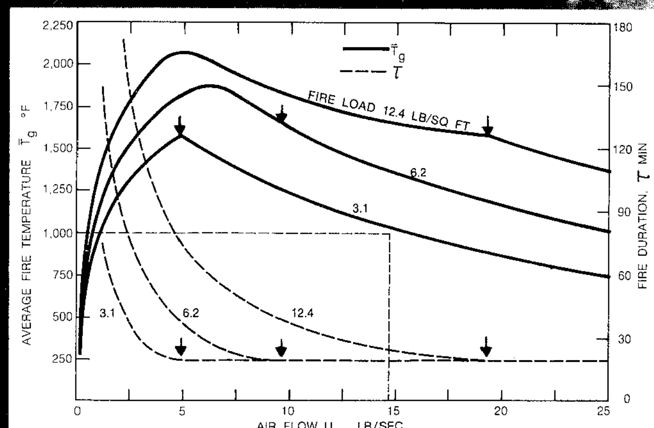

FIG. 6 AVERAGE FIRE TEMPERATURE AND FIRE DURATION
(ARROWS INDICATE CRITICAL AIR FLOWS)

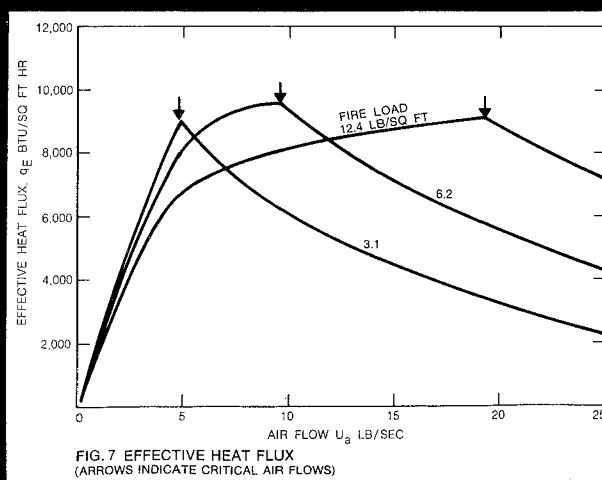

FIG. 7 EFFECTIVE HEAT FLUX
(ARROWS INDICATE CRITICAL AIR FLOWS)

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