The Severity of Fires in Steel-Frame Buildings

L. G. SEIGEL

FIRE SEVERITY is a term that has been used to describe the destructive potential of a fire in a building. It has commonly been expressed as a function of time and temperature, and standard time-temperature relationships have been developed to establish uniform procedures for testing structural members of buildings exposed to fire. In the United States, the accepted standard is the time-temperature curve described by the American Society for Testing and Materials in Standard E119 (Fig. 1). Other countries have developed similar but not identical specifications for fire severity.

The ASTM curve was adopted in 1918 as a result of conferences involving 11 organizations representing technical societies, testing laboratories, insurance underwriters, and fire-protection associations. It was intended to represent the fire severity likely to occur in the complete burnout of the contents and structure of a typical brick, wood-joisted building. About 10 years after the adoption of the standard, the National Bureau of Standards conducted burnout tests in two old brick buildings that were scheduled to be demolished in Washington, D. C. Very intense fires developed quickly, and the walls collapsed in about half an hour. Therefore, little data on fire intensity or duration were obtained. However, two temperature measurements taken before the walls collapsed indicated a severity much greater than the standard curve (Fig. 2). But the data were very limited, and the curve established by the committee was retained as the standard.

About 1940, the Bureau conducted another series of burnout tests in two specially-constructed fire-resistive buildings to obtain further data on fire severity. The buildings were furnished to represent different occupancies with fire loads ranging from 12 to 55 lbs/sq ft. Ventilation could be adjusted by regulation of louvers in the window openings. The results of these tests,[1] along with some data from European tests in structures of similar size,[2] are in reasonable agreement with the standard (Fig. 3). Although the variable nature of real fires is clearly evident, the maximum temperatures

L. G. Seigel is Associate Research Consultant, United States Steel Corporation, Applied Research Laboratory, Monroeville, Pa.

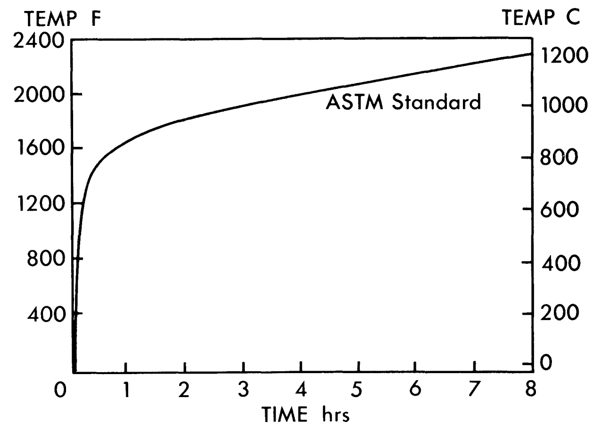

Fig. 1. ASTM E119 Standard Time-Temperature Curve

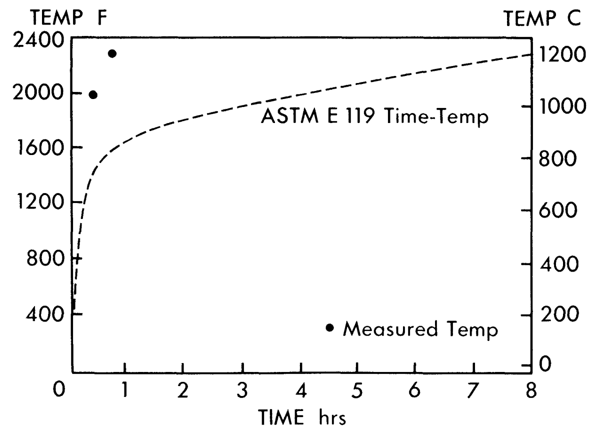

Fig. 2. Temperature in an actual fire

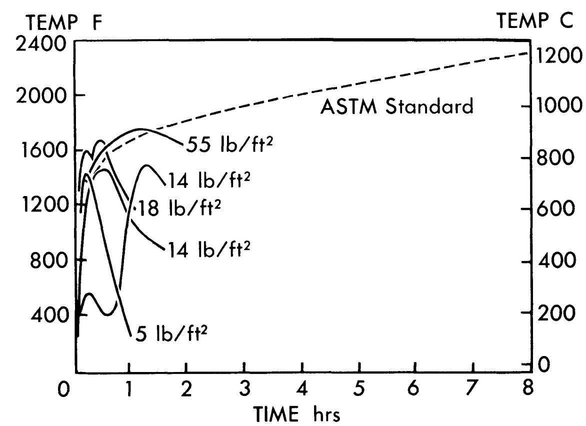

Fig. 3. Temperature attained in test fires

reached were not significantly greater than indicated by the ASTM curve. But none of these fires maintained high intensity for a long period of time. Even in the case of the 55 lbs/sq ft fire load, the temperature started to decrease after about 75 minutes. Therefore, the continually rising temperature characteristic of the standard curve for a time greater than about an hour and a half was not demonstrated. However, it should be recognized that most of these tests were conducted in small buildings with a limited number of windows and that fires in larger buildings with adequate ventilation could have considerably different characteristics.

In a steel-frame office building, for example, the fire load may consist primarily of furnishings and decorations that can be ignited readily if a fire develops. A well-ventilated fire in such a building will tend to reach its maximum temperature quickly and will usually burn out in a short time because there will be no contribution of fuel from the incombustible structure. Recent tests of fires in room-size compartments, conducted in England[3] (Fig. 4), support this statement and indicate that both temperature and duration depend on the amount of combustible material available to burn. However, in view of the limited scale of these tests, there is need to obtain further information on the characteristics of fires in large buildings where there may be extensive areas without permanent partitions.

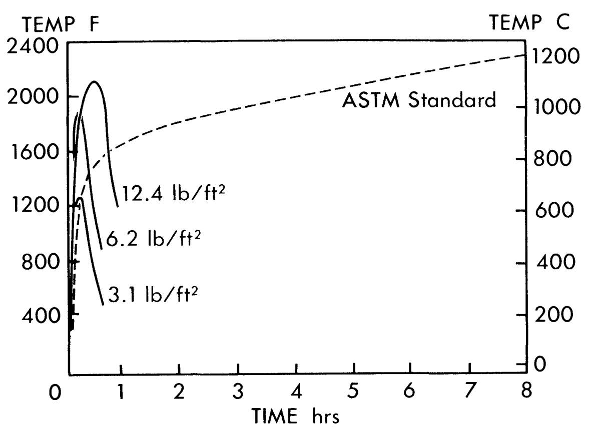

Fig. 4. Temperatures in compartment fires

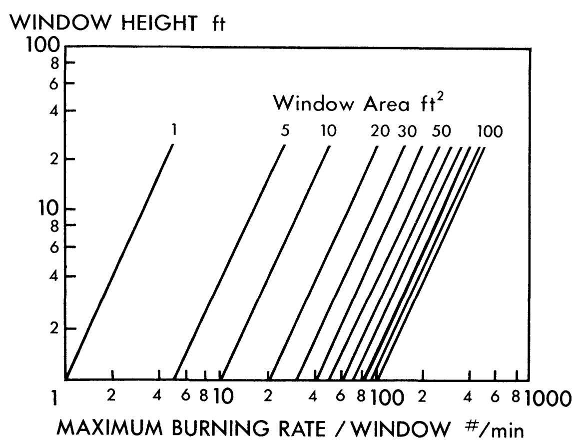

Fig. 5. Maximum burning rate for fires in enclosures with a single opening

Since such large-scale tests would be both expensive and difficult, a thermodynamic analysis is being developed to estimate the temperature and duration of fires in buildings of any size. The basis for this analysis is a heat balance that requires an accounting of the total energy available from the combustible material in the building. All of the important aspects of combustion and heat transfer during the fire must be considered, but reasonable assumptions must be permitted because of the large number of variables and the extremely complex processes involved in actual building fires.

A mathematical statement of the heat balance for a fire in a building is given in Equation (1).

$$rE = c_p(T_f - T_a)Gr + Q_sA_s + \sigma F \epsilon T_f^4 A_w \qquad (1)$$

where

A_s = Surface area of exposed building elements, ft²
A_w = Window area, ft²
c_p = Specific heat of hot gases leaving building, Btu/(lb F)
E = Energy released from fire load, Btu
F = Geometric factor for radiation
G = Weight of gases leaving building, lbs/hr
Q_s = Heat absorbed by exposed surface of building elements, Btu/(hr ft²)
r = Burning rate, lbs/hr
T_f = Fire temperature, °R
T_a = Ambient air temperature, °R
ϵ = Emissivity of radiating surface
σ = Stefan-Boltzmann constant

Essentially this equation states that the energy available from the fire load is equal to the energy carried out of the building by the smoke and hot gases plus the energy absorbed by the noncombustible parts of the building exposed to the fire plus the energy radiated from openings in the building. Some of the terms of the equation depend on the dimensions of the building, and these may be readily evaluated for any specific application. But, the burning rate, r, the heat absorption rate, Q_s, and the quantity of hot gases leaving the building, G, are not easily determined. Therefore, a discussion of these variables is in order.

The burning rate depends on the amount of combustible material, its surface area, its thermal and physical properties, and the amount of air available for the combustion process. For fires in enclosures that have a single opening in one wall, it has been demonstrated that the rate of burning depends on the dimensions of the opening. This rate may be estimated by using Fig. 5

which was developed from data reported by Law,[4] Gross and Robertson,[5] and Thomas.[6] This figure may be used to estimate burning rates for building fires that have restricted ventilation due to limited window openings. However, it must be recognized that this rate of burning will occur only if an adequate quantity of fuel is available in the enclosure. For small fire loads and large window openings, the conditions of free burning fires may exist. For such conditions, combustion is not limited by air supply, and the rate of burning depends on the surface area and the thermal and physical properties of the combustible material in the building. Although free burning data is needed for all materials normally used in building construction and furnishing, most of the information available is for wood cribs. Therefore, burning rates for the free burning of wood are shown in Fig. 6. This figure was prepared from data reported by Gross and Robertson,[5] for wood cribs constructed of different size elements. Burning rates obtained from Fig. 6 represent the maximum obtainable for a given stick size independent of the spacing of the sticks in the crib. Similar rates might be expected in a fully developed fire in a building.

By the combined use of Figs. 5 and 6, an estimate may be made for the value of r required for the solution of Equation (1). Then, if Q_s and G can be determined, the equation can be solved for the fire temperature, T_f. Unfortunately, little data is available to assist in the determination of either of these terms. Therefore, a specific solution of Equation (1) cannot be obtained at this time. However, a solution of the form shown in Fig. 7 may be obtained if Q_s and G are treated as variables.

The range of values used for G in Fig. 7 was based on the air quantity required for the combustion of wood with a generous allowance for excess air due to wind and other sources of air supply. The importance of G on the duration and intensity of a fire is clearly evident from the figure, and more information about the air flow in actual building fires would be very useful.

To establish a range of values for Q_s, it was necessary to obtain data on the rate of heat transfer at the surface of various materials exposed to fire. Figure 8 shows estimates for three materials exposed to the standard time-temperature curve. The estimates were based on temperature gradients at the exposed surface of the material. The gradients were determined by use of an analog computer which was developed to determine the temperature gradient at the surface of a material exposed to the standard time-temperature curve. Then, by use of this gradient, the heat transfer at the surface was estimated for three different materials. The results, shown in Fig. 8, suggest a range of 4000 Btu/hr sq ft to 15,000 Btu/hr sq ft for the heat absorption rate at the surface of a building material exposed to fire. The effect of this range of heat absorption may be observed by reference to Fig. 7.

Although Fig. 7 does not provide specific values for the intensity and duration of a fire, there is a definite indication that high intensity fires in buildings must be anticipated. Therefore, the severity of such fires and their effect on building materials and structures should be carefully considered. One commonly-used method of evaluating fire severity in terms of the standard curve is based on the "equal area principle." This method

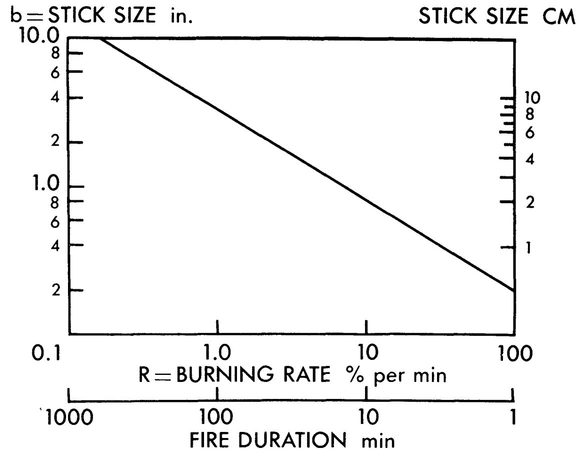

Fig. 6. Maximum burning rates for square stick wood crib fires

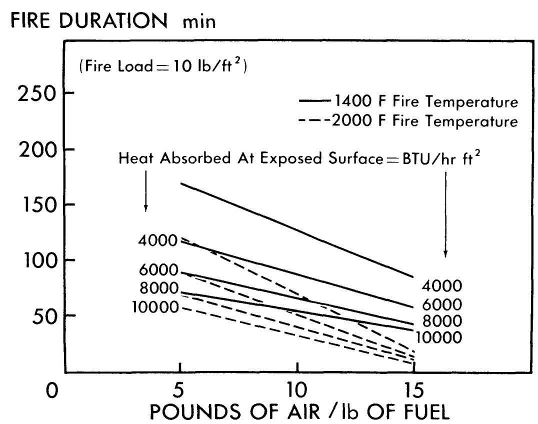

Fig. 7. Estimated fire intensity and duration in a large building

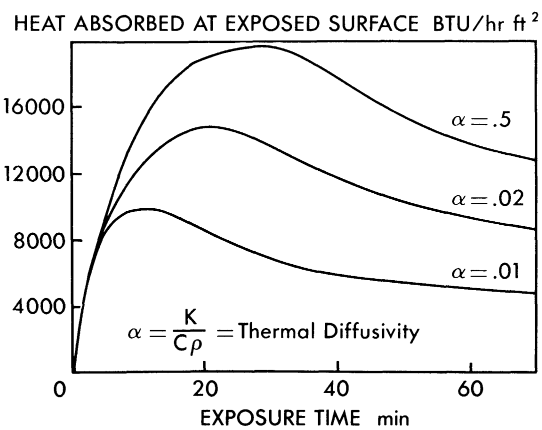

Fig. 8. Heat absorbed by surfaces exposed to ASTM E119 fire test

assumes that the severity of an actual fire will be the same as a standard fire if the areas under the time-temperature curves are the same for both fires. However, this is not satisfactory for large deviations from the standard curve because of radiation effects and certain factors related to the materials exposed to the fire.

Since the radiant intensity of a fire is proportional to the fourth power of the absolute temperature, small increases in temperature will cause relatively large increases in intensity, and therefore, materials subjected to higher-temperature fires will have a much more severe exposure than materials exposed to lower temperatures. For example, a 2000°F constant temperature fire of 20-minute duration could have a radiant energy potential eight times as much as a 1000°F fire lasting 40 minutes. But both fires would be considered to have the same severity based on the "equal area" concept. If the temperatures are high enough, explosive spalling of concrete and destructive shrinkage of gypsum may result after only limited exposure. Other materials may also be seriously deteriorated, so that they cannot perform their intended function for the duration of the fire.

In view of these considerations, it is apparent that a high-intensity short-duration fire may be more severe than a low-intensity one that lasts for a longer time. However, it does not appear possible to describe severity in terms of intensity and duration alone. The characteristics of the material exposed are also important. A specific fire load in a given building may result in fires of different intensity and duration depending on many uncontrolled factors at the time of the fire. Under one set of circumstances, a 30-minute fire of 2300°F average intensity may occur while under other conditions a fire of 1600°F average intensity may last 50 minutes. The effects of these exposures on a protected steel structural member may be radically different depending on the type of protective material used. In the case of the short-duration, high-temperature exposure, the protective material may fail structurally and direct exposure of the steel could result. But the same material may demonstrate excellent performance when subjected to the lower-temperature fire.

Therefore, further study appears necessary to determine conditions of maximum severity for testing fire-protective materials. One possible improvement in the test procedure might be the use of exposure curves such as shown in Fig. 9 instead of the standard curve now in use. Each exposure curve would represent the maximum intensity and duration anticipated for a given occupancy or fire load.

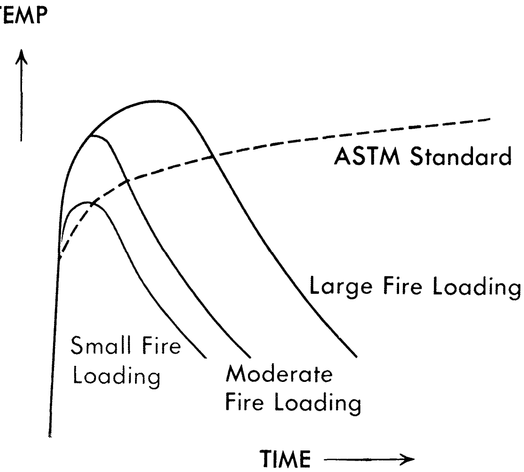

Fig. 9. Suggested severity curves for fire tests

Under a testing procedure using such exposure curves, fire-resistance performance would be given in terms of a building occupancy class or fire load instead of hourly ratings such as are commonly used today. This could lead to a simplification of building codes and if the exposure curves are carefully determined to represent maximum severity, the ratings obtained could be more reliable than those obtained under present test methods.

REFERENCES

1. Fire Protection Handbook, 12th Edition, *National Fire Protection Association, 1962.*
2. *Bongard, W.* Fire Tests on Exterior Steel Columns, *Der Stahlbau, May 1963, pp. 139–A6.*
3. *Butcher, E. G., Chitty, T. B., and Ashton, L. A.* The Temperature Attained by Steel in Building Fires, *Fire Research Technical Paper No. 15, Her Majesty's Stationery Office, London, 1966.*
4. *Law, Margaret* Heat Radiation from Fires and Building Separation, *Fire Research Technical Paper No. 5, Department of Scientific and Industrial Research and Fire Offices' Committee, Joint Fire Research Organization, Her Majesty's Stationery Office, London, 1963.*
5. *Gross, D. and Robertson, A. F.* Tenth Symposium (International) on Combustion, *pp. 943–948, The Combustion Institute, 1965.*
6. *Thomas, P. H.* Research, *13, 69, London, 1960.*