GENERAL DISCUSSION

Ove Pettersson[1] *(written discussion)*—In the paper "Perspective on Method of Assessing Fire Hazards in Buildings", presented by J. E. Ryan, the necessity of future development towards a functionally more well-defined fire engineering design procedure is strongly stressed, taking into account the influence of the specific properties of the fire load and of the geometrical, thermal, and ventilation characteristics of the fire compartment. A step in the direction of such a development has been taken in the current Swedish Standard Specifications[*1*] by introducing different alternatives of structural fire engineering design, leading to different degree of accuracy and amount of engineering design work.

One alternative is related to the internationally prevalent standard heating curve for the gastemperature of the fire compartment combined with a subsequent cooling period, specified by a linear rate of temperature decrease of 10 deg C per minute.

A second alternative is characterized by a gastemperature rise-time curve (ϑ_t–t) for the heating period, which depends on the opening factor $A\sqrt{h}/A_t$ of the fire compartment according to Fig. 1, where

A_t = the total area of the surfaces bounding the compartment (m^2),
A = the total area of the window and door openings (m^2),
h = the mean value of the heights of window and door openings (m) weighed with respect to each individual opening, and
ϑ_0 = the gastemperature at the time $t = 0$.

The length of the heating period or the fire duration T (min) is given by the formula

$$T = \frac{qA_t}{25A\sqrt{h}} \tag{1}$$

where: q = the fire load, defined as the corresponding heat value per unit area of the total surface bounding the compartment (Mcal/m^2).

For the cooling period is specified, as in the first alternative, a linear rate of temperature decrease of 10 deg C per minute, if not, some other characterization

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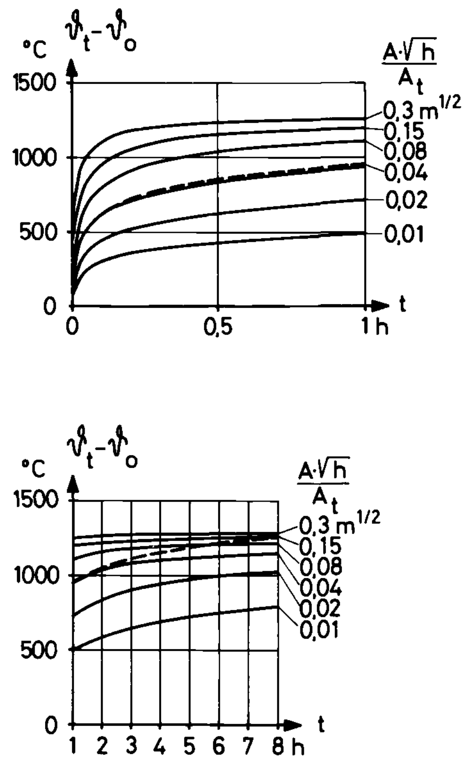

--- Standard curve according to ISO R834

FIG. 1—*Gastemperature rise-time curves of the heating period for different values of the opening factor according to Swedish standard specifications* [1].

can be proved to be more correct. This second alternative is permitted for use when the fire load is mainly of the wood fuel type.

As a result of studies, recently published by Magnusson and Thelandersson[2], a more precise knowledge exists for the gastemperature-time curve of the complete process of the fire development, including the cooling period. This knowledge comprises gastemperature-time curves for varying fire load q, opening factor of the fire compartment $A\sqrt{h}/A_t$, and thermal properties of the structures surrounding the fire compartment. The curves are permitted as a basis for structural fire engineering design according to the current Swedish Standard Specifications. The curves are exemplified by Fig. 2 which shows some gastemperature-time curves for a fire compartment with surrounding structures, 20 cm in thickness and made of a material with a thermal conductivity $\lambda = 0.7$ kcal/m/h/deg C and a heat capacity $\gamma c_p = 400$ kcal/m^3/deg C as representative

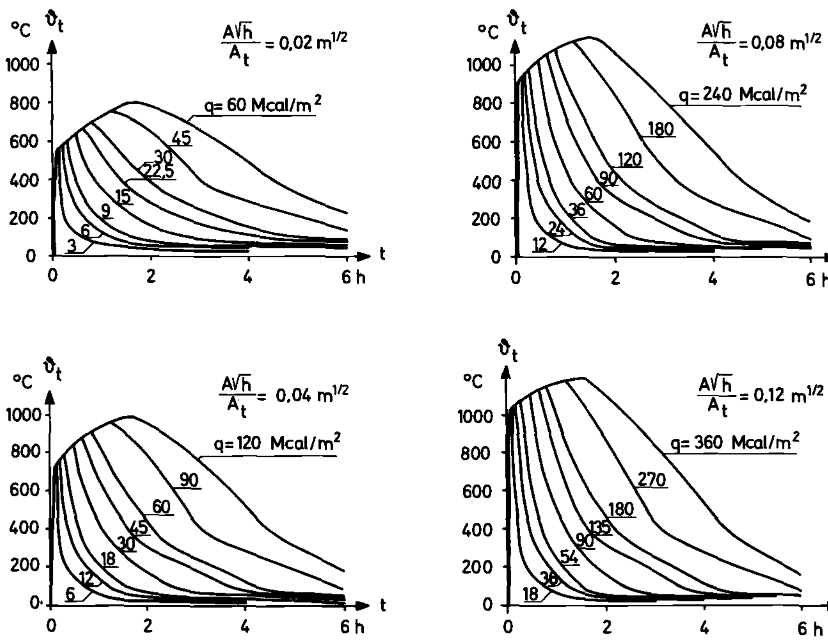

FIG. 2–*Gastemperature rise-time curves of the complete process of fire development for different values of the opening factor and the fire load. The curves assume an initial temperature of 20 C.*

average values within the temperature range associated with fires. The curves, which for the heating period provide approximately the same temperature values as the curves in Fig. 1, have been calculated from the heat and mass balance equations of the fire room on the basis of the quantity of released heat per unit of time, determined from the theoretically analyzed results of a great number of full scale tests with wood fuel fires in enclosed spaces. The gastemperature rise-time curves, according to the figures, constantly have been determined on the assumption that the fire is ventilation controlled. For fuel bed controlled fires, such a simplifying assumption leads to a fire engineering design which will be on the safe side in practically every case. (For a further discussion of this particular problem, see Refs *2* to *4*.)

As a third alternative, the current Swedish Standard Specifications permit a structural fire engineering design on the basis of a gastemperature-time curve, calculated for each individual case from the heat and mass balance equations–or determined in some other way–with regard taken for the combustion characteristics of the fire load, the ventilation characteristics of the fire compartment, and the thermal properties of the surrounding structures of the fire compartment.

Generally it is prescribed for a fire engineering design of loadbearing and separating structures to be proved that the structures during the fire are able to fulfill the functional requirements stipulated. For a load-bearing structure that means a proof that the load-bearing capacity does not decrease below the design load (or some other prescribed load), multiplied by a required factor of safety, during neither the heating period nor the subsequent cooling period of the process of fire development. For a separating structure the requirements stipulated mean that it must be verified that during the complete process of fire development flames or hot gases will not pass through the structure and that the temperature increase on the unexposed face of the structure does not exceed a specified value.

For the first alternative of fire engineering design, mentioned above, the proof of the fulfillment of the prescribed requirements is connected to a very rough system of classification, based on the standard fire resistance test of elements of building construction.

Related to the second or third alternative a fire engineering design of a load-bearing structure comprises the following main components [*3,5-8*].

(*a*) The choice, in each particular case, of representative combustion characteristics of the fire load.

(*b*) The determination for these combustion characteristics of the gas-temperature-time curve and the convection and radiation properties of the complete process of fire development, taking into account the geometry of compartment, the size and shape of window and door openings, and the thermal characteristics of the structures enclosing the compartment.

(*c*) The determination of the corresponding temperature-time fields in the structure or the structural element, exposed to fire.

(*d*) The determination—on the basis of data according to (*c*) and the strength and deformation properties of the structural materials in temperature range, associated with fires—of the time for collapse at prescribed loading or, alternatively, of the minimum load-bearing capacity of the structure or the structural element for the process of fire development.

In a fire engineering design for an adjacent structure or structural element the design component (*d*) usually is out of interest.

In making a structural fire engineering design according to the principles outlined above applicable for the structural engineer, it is necessary to supplement the procedure with design diagrams for different types of structures or structural elements. The design diagrams required must comprise information for facilitating, on one hand, a calculation of the determining temperature of the fire exposed structure, on the other, a translation to the corresponding static behavior and load-bearing capacity of the structure. At present such design diagrams are systematically produced in Sweden and examples of knowledge available are referred in Figs. 3 to 7.

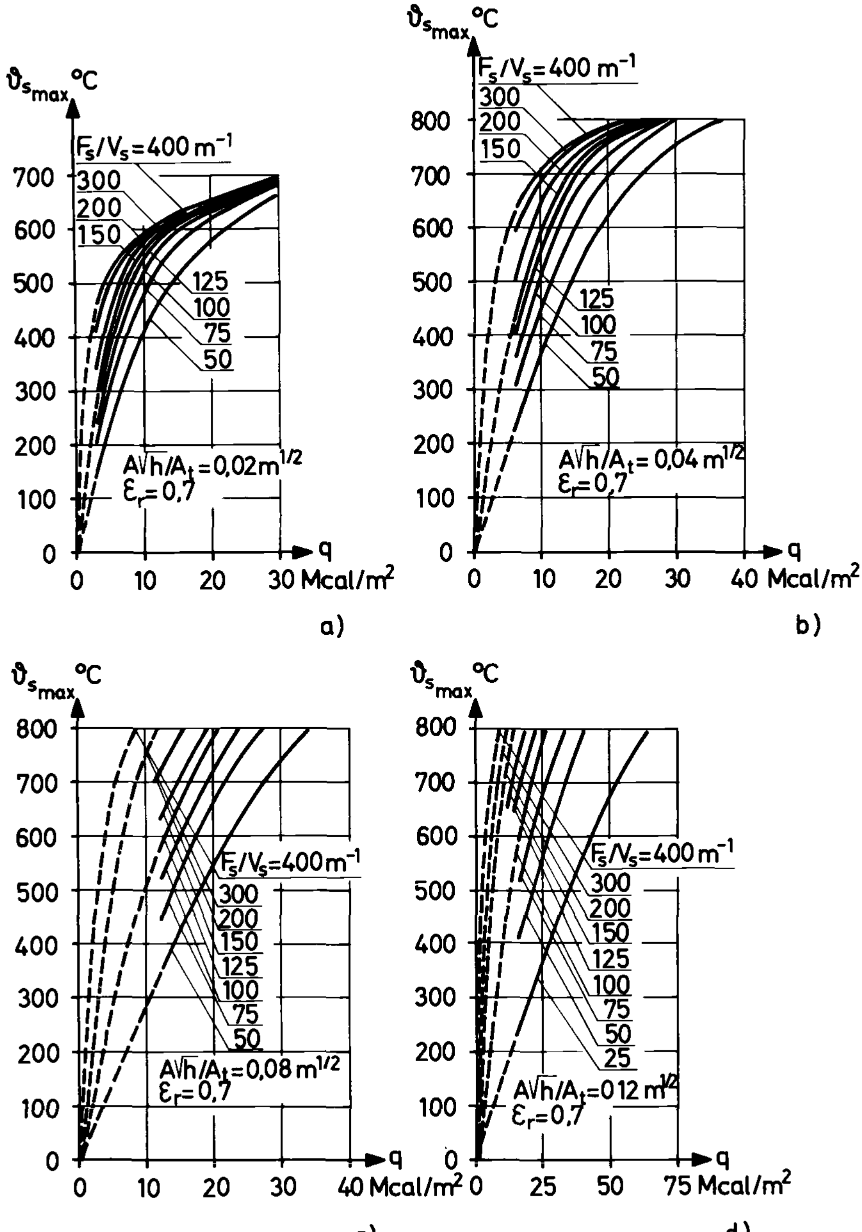

FIG. 3—*Maximum temperature for a fire-exposed, noninsulated steel structure at varying opening factor, fire load, and structural characteristics. The curves take into account the influence of the cooling phase of the process of fire development and assume an initial temperature of 20 C.*

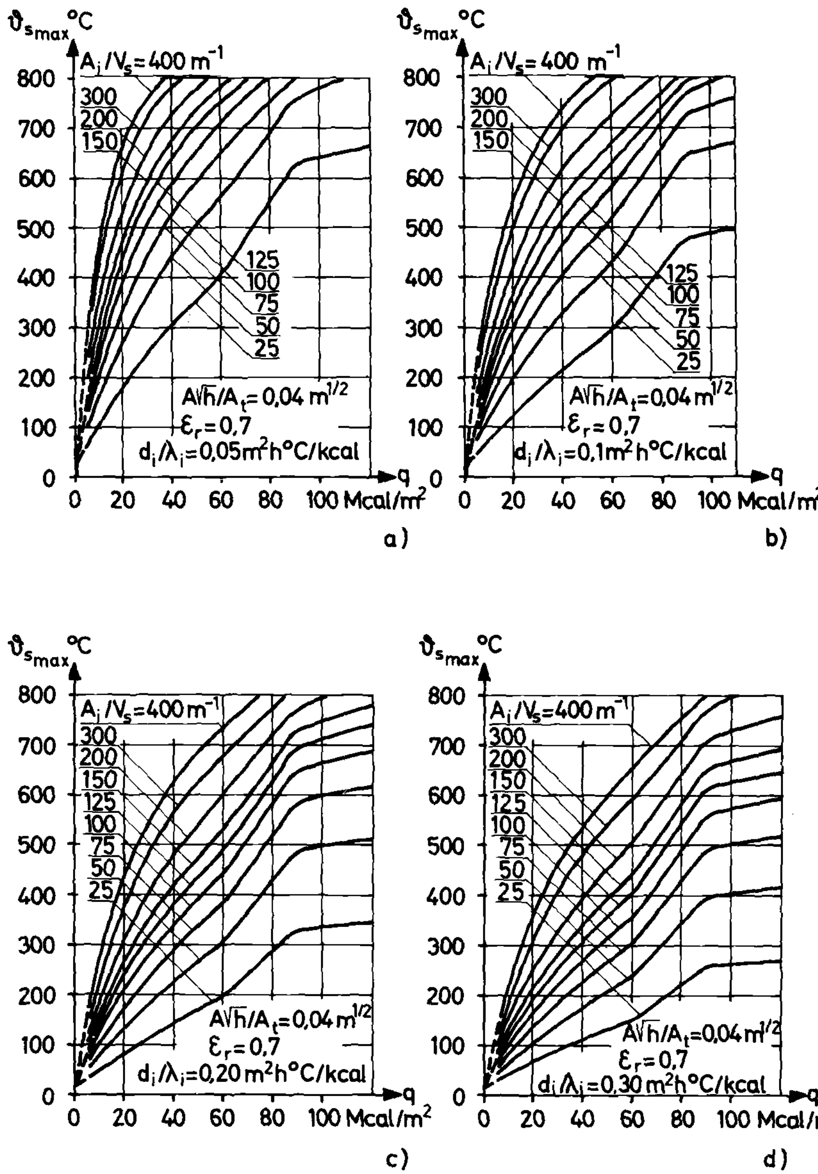

FIG. 4—*Maximum temperature for a fire-exposed, insulated steel structure at varying opening factor, fire load, and structural characteristics. The curves take into account the influence of the cooling phase of the process of fire development and assume an initial temperature of 20 C.*

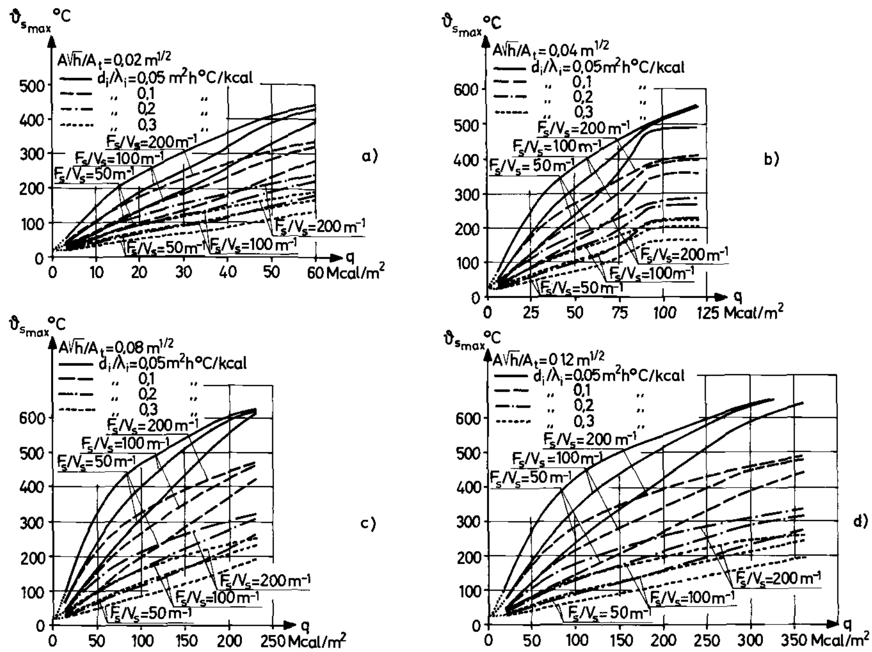

FIG. 5–*Maximum temperature for the steel beams of a fire-exposed ceiling structure, composed of a reinforced concrete slab, load-bearing steel beams, and an underlying insulation, at varying opening factor, fire load, and structural characteristics. The curves take into account the influence of the cooling phase of the process of fire development and assume an initial temperature of 20 C.*

In Fig. 3*a*-*d*[*8*] design curves are presented, directly giving the maximum steel temperature $\vartheta_{s_{max}}$ for a fire exposed, noninsulated steel structure at varying opening factor $A\sqrt{h}/A_t$, fire load q, and quotient F_s/V_s. F_s is the fire exposed surface and V_s the volume of the steel structure per unit length, the emissivity $\epsilon_r = 0.7$. The diagrams are based on gastemperature-time curves of the fire compartment according to Fig. 2. For fire compartments with other thermal characteristics of the surrounding structures, the same design diagrams for $\vartheta_{s_{max}}$ can be used in combination with rules for a transformation from one fire compartment to another via fictitious values of the fire load q and the opening factor $A\sqrt{h}/A_t$.

Under the same conditions of fire exposure, the design diagrams in Fig. 4*a*-*d*[*8*] show the maximum steel temperature $\vartheta_{s_{max}}$ for an insulated steel structure at varying fire load q, and quotients A_i/V_s and d_i/λ_i. Then A_i is the mean jacket surface area of the insulation per unit length of the structure, d_i the thickness of the insulation, and λ_i the thermal conductivity of the insulating

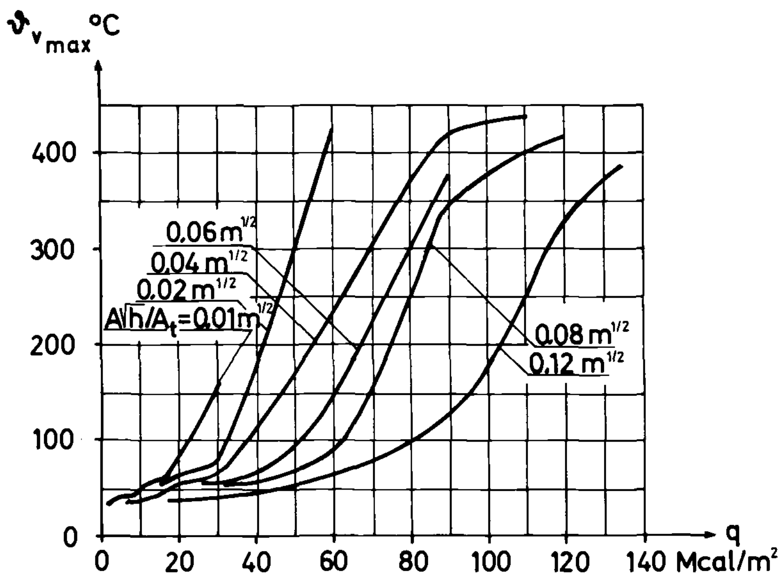

FIG. 6—*Maximum temperature of the unexposed face of a fire-exposed separating structure, composed of a non-load bearing steel frame, insulated on both sides by two gypsum plates, at varying opening factor and fire load. The curves take into account the influence of the cooling phase of the process of fire development and assume an initial temperature of 20 C.*

material. The curves reproduced are related to an opening factor $A\sqrt{h}/A_t = 0.04$ $m^{1/2}$ and an emissivity $\epsilon_r = 0.7$.

Fig. 5*a-d* [*8*] illustrates the corresponding temperature conditions for a ceiling structure, composed of a reinforced concrete slab, load-bearing steel beams, and an underlying insulation of thickness d_i. The figure shows the maximum temperature $\vartheta_{s_{max}}$ for the steel beams of the structure at varying opening factor $A\sqrt{h}/A_t$, fire load q, and quotients F_s/V_s and d_i/λ_i.

In Fig. 6 [*8*], the insulating properties are illustrated for a partition, composed of a non-load bearing steel frame insulated on both sides by two gypsum plates with an individual thickness of 13 mm. The design diagram gives the maximum temperature $\vartheta_{v_{max}}$ of the unexposed face of the structure, when fire exposed on one side, at varying opening factor $A\sqrt{h}/A_t$, and fire load q. The curves have been calculated with regard to the effect of the disintegration of a gypsum plate at certain temperature conditions.

The problem of translation from a determining temperature to a load-bearing capacity of a fire exposed structure is exemplified fragmentarily in Fig. 7*a-d* [*9*]. The curves in these diagrams give the variation with steel temperature ϑ_s of the relationship between the buckling stress σ_k and the slenderness ratio λ for fire

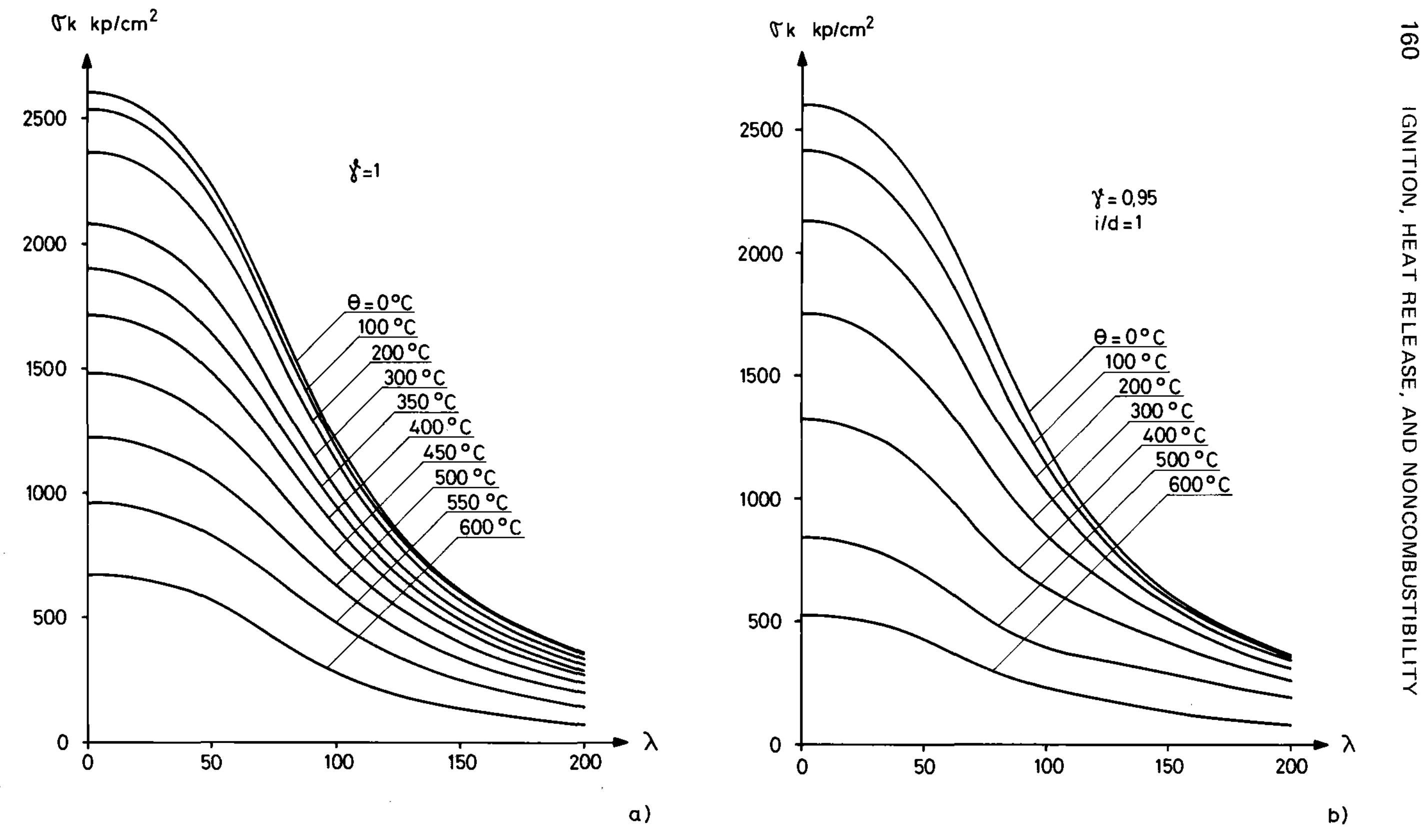

FIG. 7—*Variation with the steel temperature of the relationship between the buckling stress and the slenderness ratio for fire exposed, axially compressed columns, partially restrained to longitudinal expansion and made of steel having a yield point stress at ordinary room temperature* $\sigma_S = 2600\ kp/cm^2$.

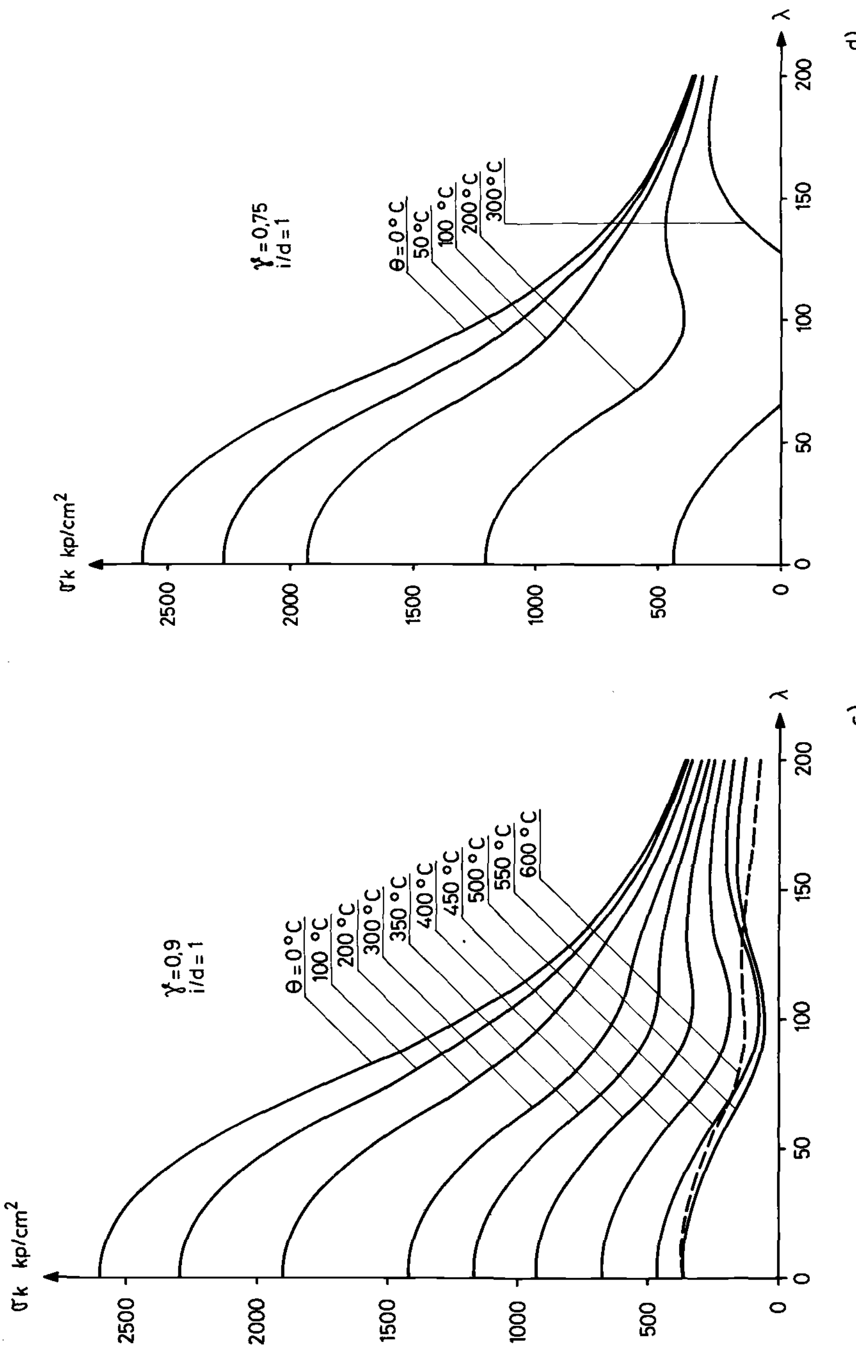

FIG. 7–(*Continued.*)

exposed, axially compressed columns made of steel having a yield point stress at ordinary room temperature σ_s = 2600 kp/cm^2. The different diagrams refer to varying degree of restraint to longitudinal expansion during the fire. The degree of axial restraint is characterized by a coefficient γ, giving the quotient between the possible longitudinal expansion and the completely unrestrained elongation of the fire exposed column. Accordingly, $\gamma = 1$ corresponds to no longitudinal restraint at all, and $\gamma = 0$ to a full restraint to axial expansion of the column. The σ_k–λ curves have been calculated for an initially deflected and excentrically loaded column with imperfections according to Dutheil [*10*] on the basis of data on the change of the 0.2 stress and the modulus of elasticity with the temperature ϑ_s for mild structural steel, received in tension tests at a very slow loading rate which implies that some effect of short-time creep has been considered [*11*]. For $\gamma = 1$, the σ_k–λ relationship is independent of the form of the cross section of the column. For $\gamma \neq 1$ the σ_k–λ relationship varies with the quotient i/d, where i is the radius of gyration and d the distance from the gravity center axis to the edge of the section of the column with maximum compressive stress. The curves reproduced in Fig. *7b-d* are for $i/d = 1$.

The following concluding remarks can be given. The functionally more well-defined procedure of structural fire engineering design, briefly described and exemplified above, coincides in a stimulating manner with the present development of the building codes and regulations towards functionally more well-defined requirements. The design procedure is not connected to any need of classification and gives a low priority to the present standard fire resistance test of elements of building construction. In the design procedure, the results of such standard tests can be used either for a confirmation, point by point, of the theoretical treatment, or as a source of basic information, necessary for the calculations. In those cases, when this basic information depends on the detailed characteristics of the process of fire development, for instance, basic data concerning the disintegration of structural materials, enlarged short-time effect of creep and shrinkage, effect of crack formation and spalling, behavior and strength of fastening devices for different types of insulation, the design procedure can necessitate experimental investigations at gastemperature-time curves diverging from the standard time-temperature curve. In most cases, the data required can be determined by essentially less extensive experiments than the standard fire resistance test.

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GENERAL DISCUSSION

H. L. Malhotra[1] (*written discussion*)—The natural and intuitive inclination to associate noncombustibility with safety is understandable. It runs strongly throughout insurance requirements, fire brigade advice, and building code specifications. When systematic knowledge on the behavior of fires and factors which affect their growth and development was lacking, the use of noncombustible materials and constructions for maximum safety was a defensible approach. Now that we know a little more of the way in which materials react to a fire situation, how their individual characteristics and those of the environment in which they exist jointly influence the fire pattern, it is opportune that we should examine the logicality of specifying noncombustibility as a sole safety criterion and how justifiable is the reliance placed on it.

We have been told that noncombustibility implies that a given material is, by and large, of an inorganic origin and inert in behavior at temperatures up to 750 C. The test method may be based on the classical technique for determining the calorific value, or perhaps a modification of it allowing larger samples to be used, or comparatively bigger samples may be decomposed in a heated atmosphere to see if they burn visibly or create conditions synonymous to burning.

It is doubtful if any of these methods can fulfill one of the primary requirements of any fire test, that is to give an accurate indication of the behavior of the material in a real fire situation. The test procedure adopted by the International Standards Organization (ISO) comes nearest to meeting this criterion but even this is far from being fully satisfactory. The ISO test tells us that a noncombustible material will have low calorific value, below about 500 cal/g, and that it will release this potential heat at a measurably slow rate. The advantages of using a piece of the material rather than a powdered homogenous sample bearing little resemblance to its use in a building are obvious but even so the representation is inadequate.

One of the major failings of noncombustibility techniques lies in their negative nature. Procedures tell us what a material will not do rather than provide a guide to its behavior in a fire. For example, a well designed flammability test indicates the performance to be expected from materials and products on a performance scale. If we have available representative, environment linked,

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reliable, and reproducible flammability tests, it is doubtful if there is any need to have a separate test for noncombustibility. We know that the important characteristics of a material which are relevant to its fire behavior are ignitability, rate of heat release, and the total heat content or the duration for which the heat will be released. I suggest that if we have suitable procedures for measuring these factors we shall find that noncombustibility is one end of the performance scale. Obviously we do not really need a separate test for this purpose.

It will be some time before we do have agreed techniques for the flammability or the reaction to fire aspects of material behavior and we therefore need to have a test for the interim period. I strongly suggest that the ISO technique is the most useful method which we can use, let us use it, let us not embark on time and energy consuming exercises to subject it to analytical and philosophical surgery to try and make it into a highly refined tool. Let us not develop closely related alternatives for suspect technical reasons. We have a great many demands on our limited facilities which should be channelled into some rewarding areas.

At the same time it is necessary to take a close look at the building codes and regulations to see if proper use is being made of the noncombustibility requirements. There are a few situations in a building which do require the use of inert materials, I suspect there are many others where noncombustibility is specified but in fact a flammability test could be of use without any loss of safety. It is not intended that we lower the safety standards in building but that we use the right tools to achieve our objectives.