Principles of Fire Engineering Design and Fire Safety of Tall Buildings

Pettersson, Ove

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LUND UNIVERSITY

PO Box 117
221 00 Lund
+46 46-222 00 00

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PRINCIPLES OF FIRE ENGINEERING DESIGN AND FIRE SAFETY OF TALL BUILDINGS [1)]

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Technical Committee No. 8
Fire and Blast

State of Art Report No. 6

PRINCIPLES OF FIRE ENGINEERING DESIGN AND FIRE SAFETY OF TALL BUILDINGS

Ove Pettersson
Prof., Dr.
Division of Structural Mechanics and Concrete Construction
Lund Institute of Technology
Lund, Sweden

From a fire engineering point of view it is natural to define a tall building as one, in which emergency evacuation is not practical and in which fire must be fought internally because of the height of the building [1]. Typical characteristics of such a building are:

- the building is beyond the reach of the fire department aerial equipment,
- the building poses a potential for a significant stack effect, and
- the required evacuation time for the building is unreasonably long.

Since in a tall building the people cannot be evacuated at a fire, it becomes fundamentally necessary to provide the building with such fire protection measures that at various levels areas of refuge with a high degree of fire and smoke resistance can be reached in a safe way at a fire in any compartment of the building.

Mainly devoted to a survey of the principles of fire engineering design and fire safety, the following report has been drawn up with the simultaneous intention to complete the other state of art reports on fire and to supply the work within Technical Committee No. 8 with some of the most essential results of the International Conference "Firesafety in High-Rise Buildings", held at Airlie House, Warrenton, Va., USA, on April 12 - 16, 1971 [1].

In the report, at first the general concept of overall fire safety will be sketched. Then a short survey will be given concerning the present knowledge of the main characteristics of the fire load, the fire spread and the complete process of fire development. On the basis of this introductory presentation some specific, important problems of high-rise buildings - such as occupant protection, life support systems, fire control and extinguishment - shortly will be discussed. In this connection, the main features of a goal oriented systems approach to building safety are reported. Finally, the principles of a structural fire engineering design will be given and fragmentarily exemplified together with a brief outline of the structural fire safety problem.

1. THE GENERAL CONCEPT OF FIRE SAFETY

The total national, annual cost of fire damage and of different measures of fire protection comprises the following main components:

- the cost of the direct fire damage,
- the cost of the indirect fire damage, i.e. effects of disturbances or interruptions in production, effects of lost markets, consequences of loss of life and opportunities for working,
- the cost of the fire prevention measures,
- the cost of the alarm systems, extinguishing systems and other fire fighting and safety devices, and
- the cost of the administration of the fire insurance companies.

With due regard to other social factors, on a community level the aspiration must be, as concerns the total fire protection investments,

- to give the fire prevention measures and the fire fighting and safety devices at a given volume of the investments such a detail design that the effect will be optimum, and
- to choose such a level of these total investments that the sum of the investments and costs of the direct and indirect fire damages will be a minimum [2] - [5].

This general principle is further illustrated by Fig. 1, in which a denotes the total cost of investments for fire prevention and fire fighting and related safety measures with a detailed cost distribution giving optimum effect, and b denotes the total cost of direct and indirect fire damages, including the administration costs of the fire insurance companies. An increase of the total cost of investments a leads to a reduced extent of the cost of fire damages b. At a certain level of the cost of the investments a, the sum of the costs a and b will be a minimum - the point A on the curve of a+b in the figure. In relation to this level of the cost a, an increase as well as a decrease of the investment costs of the total fire protection measures will cause an increase of the sum in total of the costs of fire protection and fire damages - the points B and C on the curve of a+b.

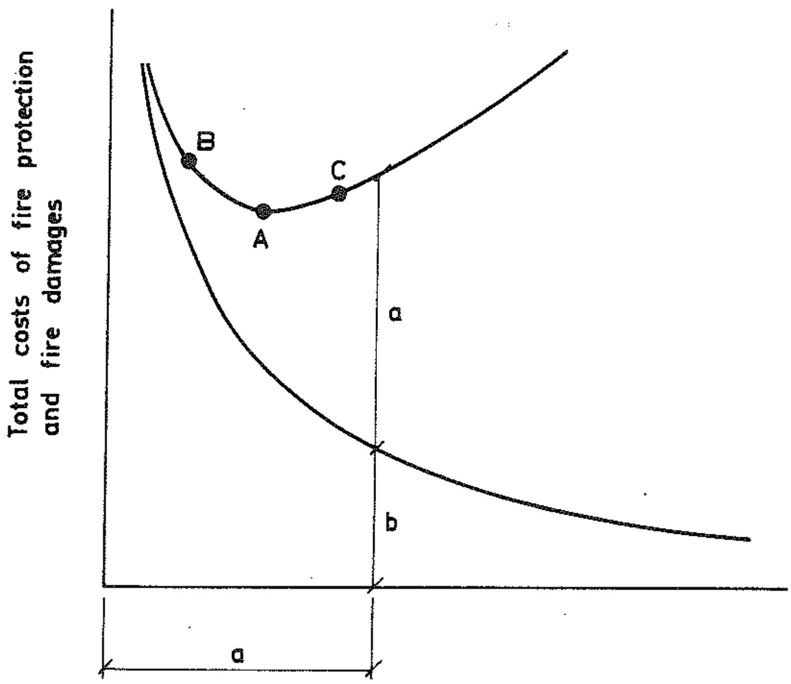


Figure 1. The relationships between the total cost of investments for fire prevention and fire fighting a, the total cost of direct and indirect fire damages b, and the sum in total of the costs of fire protection and fire damages a+b [2] - [5]

The discussion carried out above in connection to Fig. 1 for the costs of fire protection and fire damages on a community level is valid approximately unmodified also in application to, for instance a fire brigade district, an industrial area or a large industry with its own fire brigade resources, i.e. for such applications which are distinctly limited with respect to the total costs. Applied to a separate building the principle outlined must be modified due to the fact, that the investments for fire prevention and fire fighting measures for such an object constitute an integrated part of the overgrasping fire protection facilities of the community with the municipal and public resources for rescue and fire fighting as the most important component.

Ordinarily a design approach according to the described philosophy must be connected to certain requirements, as concerns a minimum standard of fire prevention and fire fighting. In application to a load-bearing structure or a partition these requirements can be illustrated a little more in detail by Fig. 2 as follows.

In this figure three basic curves (1), (2), and (3) are shown for the relationship between the requisite time of fire resistance $\underline{T}$ of a load-bearing or a separating structure and the effective fire load $\underline{q}$. The curves presuppose a given type of structure and a given fire compartment, specified by its geometrical, ventilation and thermal characteristics. The curve (1) then describes the shortest time of fire resistance, for which the structure must be designed in order to guarantee the fulfilment of the required function during the heating period of the process of fire development. According to the definition this means a fire resistance time $\underline{T}$, which for any fire load value $\underline{q}$ is equal to the duration of the heating phase of the corresponding, undisturbed process of fire development. The analogous curve (2) relates to an increased requirement of a fulfilled function of the fire exposed structure during a complete, undisturbed process of fire development, comprising the heating phase as well as the subsequent cooling phase. In the figure the fire resistance time necessary $\underline{T}$ then has been presented as the equivalent length of a heating period, giving for the actual fire compartment the same maximum influence on the structure - for a load-bearing steel structure the same maximum steel temperature - as a complete process of fire development, corresponding to the actual fire load q. Applied to a load-bearing structure the curves (1) and (2) are characterized by the condition that the load-bearing function is to be fulfilled with respect to that level of loading which is representative to the structure from a probabilistic point of view in connection with a fire exposure.

For buildings containing activities, which are particularly important from, for instance, an economical point of view, there can be the motive for a further increase of the requirements on the fire portection measures to such a level that the building can be used again after a fire, almost immediately or very soon, for the current activities in full extent. For a load-bearing structure then it must be required that the initial load-bearing capacity either will remain approximately unchanged after an exposure to a complete process of fire development or only will be reduced in such a limited extent that it can be restored to its initial value in a short time by a moderate amount of work. The curve (3) in Fig. 2 corresponds to a fire engineering design of a load-bearing structure which fulfils requirements of this level. In the figure this fire resistance quality has been transformed for any value of the fire load $\underline{q}$ to a fictitious or an equivalent fire duration $\underline{T}$, determined by that length of a heating period during which the structure can fulfil its load-bearing function at a representative load level and at a fire, characterized via the properties of the actual fire compartment. Such fire engineering requirements as expressed by the curve (3) introduce for load-bearing structures and partitions usability criteria as a complement to the conventional fire resistance criteria [5].

In ordinary applications the absolute minimum standard of the fire prevention and the fire fighting measures will be fixed by the unavoidable requirement of a

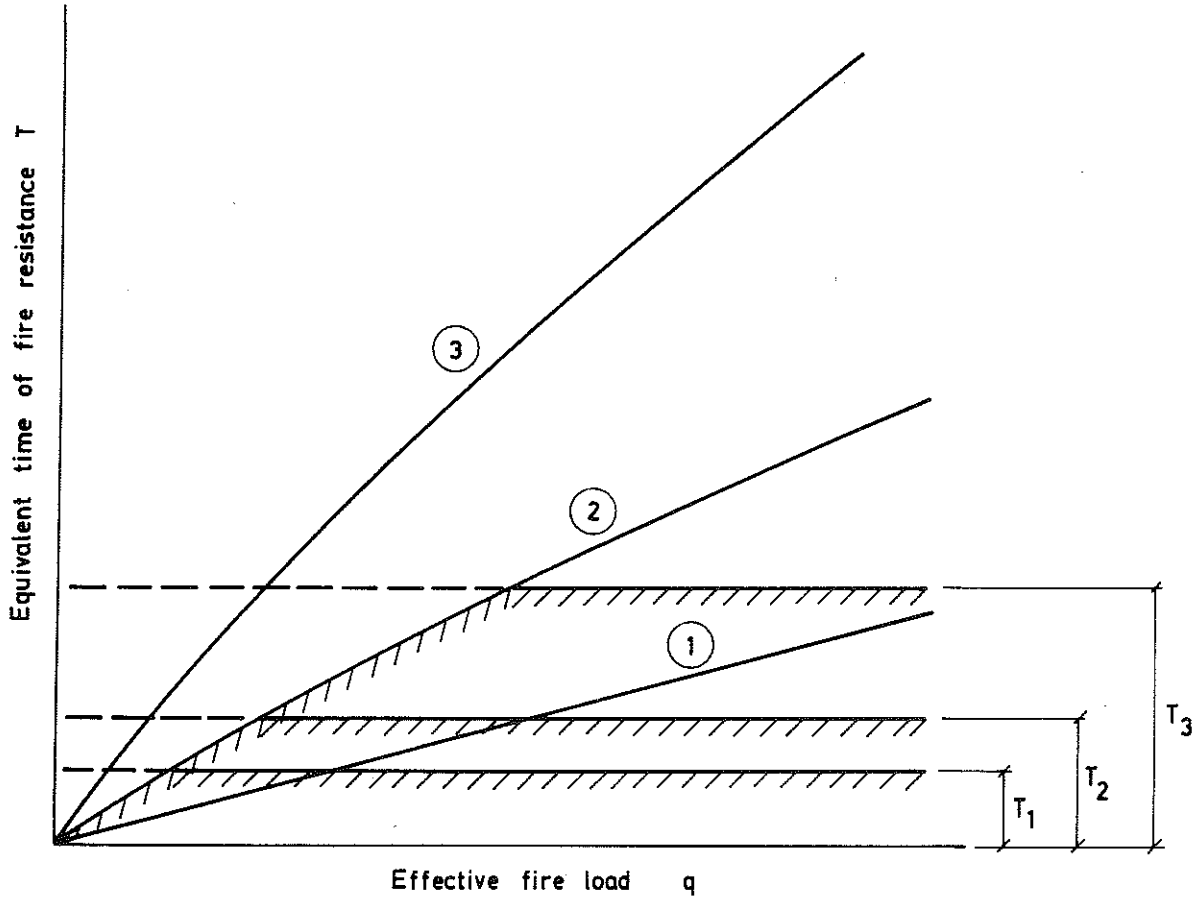


Figure 2. The relationship between the equivalent time of fire resistance T and the effective fire load q for a given type of structure and at given characteristics of the fire compartment

safe emergency evacuation of people at a fire or a safe personal movement from fire affected areas to areas of refuge. For the fulfilment of this basic requirement the building must have been given such a fire engineering design with regard to the evacuation system, the compartmentalization, and the structural integrity that the evacuation or the personal movement can be realized at a heat and smoke exposure which is not hazardous for the people. For most buildings a complete evacuation of the people will be the actual alternative. In such a case the requirement of a safe emergency evacuation of the building means that a load-bearing structure or a partition has to fulfil its function during only the evacuation time necessary T_1. In a presentation according to Fig. 2 this will lead to a minimum fire resistance time T determined by the curve (2) up to the level T_1 and for larger values of the fire load q by the horizontal line $T = T_1$. In tall buildings the necessary occupant protection at a fire must be solved by a personal movement to safe areas of refuge. As a consequence, the requirements of the load-bearing and separating structures must be increased to guarantee their functions at a prescribed safety level during either the complete process of fire development or the time necessary for the fire to be extinguished under the most severe conditions.

For buildings with a content of very vital and expensive equipment, there can be a financial motive for an increased minimum standard of the fire prevention and the fire fighting measures corresponding to a guaranteed evacuation of the people as well as parts of the equipment. To such a goal it belongs a minimum evacuation time $\underline{T}_2$, which is generally larger than $\underline{T}_1$ and for which the same principal discussion can be carried out as the above discussion concerning the evacuation time $\underline{T}_1$.

Rather often, the minimum standard level of the fire protection measures must be further increased to a smallest equivalent time of fire resistance $\underline{T}_3$, which for a load-bearing structure implies a requirement of a fulfilment of the load-bearing function up to that time at which a fire will be completely extinguished at unfavourable circumstances. With reference to Fig. 2, this will give a minimum fire resistance time $\underline{T}$ which will be determined by the curve 2 up to the level $\underline{T}_3$ and then for larger values of the fire load $\underline{q}$ by the horizontal line $\underline{T} = \underline{T}_3$. The primary cause for such a requirement is dictated by the necessity of a reasonable safety against collapse of a fire exposed structure with regard to the fire brigade people engaged in fire fighting. If then a fire exposed structure has a larger residual load-bearing capacity after cooling than the smallest load-bearing capacity of the heated structure, the requirement also guarantees the safety for the people who have to clear the building after the fire. If, however, the load-bearing capacity of a fire exposed structure continues to decrease during the cooling phase of a fire, the minimum equivalent fire resistance time of the structure must be higher than the level $\underline{T}_3$ in order to give the necessary safety for the clearing people.

A practical design of the fire prevention and fire fighting measures according to the general safety philosophy outlined above requires a very extensive basis of knowledge concerning a large amount of relevant probabilistic parameters. Examples of such parameters are:

- the probability of a fire outbreak,
- the probability of a fire giving flashover in a compartment,
- the distribution or frequency curves of the fire load and of different types of loading, representative to any point of time for a fully developed fire,
- the probabilistic characteristics of the fire compartment and the process of fire development,
- the distribution or frequency curves of the relevant material and structural component properties within the temperature range associated with fires,
- the practically unavoidable imperfections for real structural elements or structures,
- the risk that the safety codes within the field of fire prevention will not be followed in all details, and
- the functional unsafeness of the detection, warning-communication and extinguishment systems, the control systems for smoke and other combustion products and the evacuation systems.

Further complications are constituted by, for instance, precalculations of the economic consequences of different types of fire damages on buildings, equipment etc. Unfortunately, the present knowledge is extremely fragmentary concerning the parameters and influences exemplified and far from a state enabling a fire engineering design according to the principles of an overall economic optimum problem in ordinary practical applications. Even if a very extensive, purposeful and systematized research work will be initiated in the future on an international level, it must be estimated as realistic, that the requisite probabilistic informations will not be fulfilled within the next decades for a more general application of an economic-optimum fire engineering design of the summarily described structure. An important appurtenant problem comprises methods of estimating the costs of not finding out the economic-optimum solution in different applications.

In spite of such a judgement, it is essential to stress the importance, that the principle of an overall economic optimum solution always ought to be kept in mind as a goal in the background when applying the highly simplified fire engineering procedures of today for a determination of the fire protection measures. Facilitating means for following this recommendation are qualified economic analyses of successively received empirical knowledge and functionally based methods for a differentiated design, as concerns limited fire engineering problems. The differentiated fire engineering design of load-bearing structures, briefly presented in chapter 4, exemplifies such a functionally based method.

Of interest to mention in this connection are the points systems, introduced in some countries. By such systems different levels of fire safety can be defined in a qualitative way. The systems may be exemplified by the Swiss points system [6], dividing the buildings into four risk classes, and in which system the following influences can be taken into consideration:

- the amount of the fire load,
- a possible presence of explosive combustible components,
- the heigth of the individual stories,
- the heigth of the building,
- the floor area of the fire compartments,
- the design of the roof,
- the degree of fire exposure of the structural elements of the building,
- the degree of concentration of people in the building, and
- the detail characteristics of the fire fighting devices.

A second exemplification of the points systems may be given by a total fire protection system design for tall buildings which recently has been put forward in USA in the form of a summary sketch [1]. The system comprises the following eight design elements which could be combined and considered in a total system to achieve any level of fire protection:

- the detection system,
- the warning-communication system,
- the evacuation system of physical facilities,
- the structural integrity and compartmentalization,
- the extinguishment system,
- the fire loading control,
- the environmental design, and
- the proper maintenance and inspection.

Most of the design elements in such a system then are interrelated which is fragmentarily exemplified in Fig. 3, as concerns the relationship between the structural integrity and the extinguishment system. In the figure the structural integrity and extinguishment systems comprise a variation from 0 to 100 %, recognizing that the 100 % points are not attainable in actual practice. S and E define minimum standards of the structural safety and the extent of extinguishment, respectively, giving limits A and B for a practical use of the relationship. Within the section AB of the curve the design engineer can operate for an analysis of the costs of different combinations of structural integrity and extinguishment systems of equivalent resultant fire safety.

The goal oriented systems approach to building safety, summarily reported in chapter 3, can be seen as a further development of the ideas of the points systems, described above.

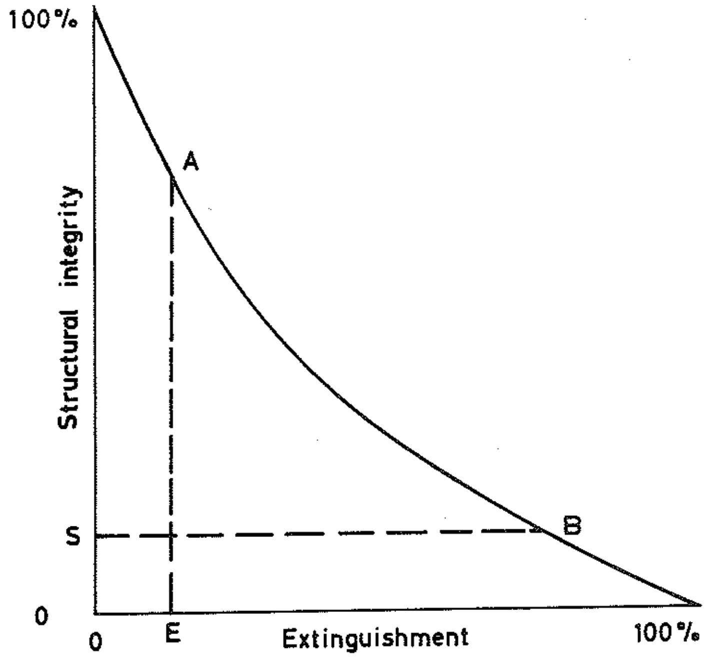


Figure 3. The relationship between the design elements "Structural integrity" and "Extinguishment" in a total fire design system [1]

2. FIRE LOAD, FIRE GROWTH, AND PROCESS OF FIRE DEVELOPMENT IN A COMPARTMENT

2.1 FIRE LOAD

Conventionally the fire load (fire load density) q_c, constituting a measure of the total quantity of combustible materials in a compartment, is defined according to the relation

$$q_c = \frac{1}{A_f} \Sigma\, m_\nu H_\nu \quad (\mathrm{Mcal/m^2}) \tag{1}$$

where A_f = the floor area (m^2), m_ν = the total weight (kg), and H_ν = the effective heat value (Mcal/kg) for each individual material ν. In some countries the fire load q_c is given alternatively as the equivalent amount of wood per unit floor area A_f.

In the current Swedish building codes and regulations the fire load q of a compartment is defined according to the modified formula

$$q = \frac{1}{A_t} \Sigma\, m_\nu H_\nu \quad (\mathrm{Mcal/m^2}) \tag{2}$$

where A_t = the total area of the surfaces bounding the compartment (m^2). Such a definition is more natural with respect to an application to the heat and mass balance equations of the fire compartment. The connection between the different fire load definitions is given by the equations

$$q_c = \frac{A_t}{A_f} q \quad (\text{Mcal/m}^2) \text{ and } q_c = \frac{A_t}{4.5A_f} q \quad (\text{kg/m}^2) \tag{3}$$

respectively.

With reference to the definitions according to Eqs. (1) and (2), internationally a large number of probabilistic studies have been carried through of the fire load in dwellings, offices, administration buildings, schools, stores, and hospitals. A comprehensive summary of recent survey data is presented in SOA Report No. 1.

A further development, leading to a more differentiated characterization of the fire load has high degree of urgency. A first step in such a direction could be a replacement of the definitions according to Eqs. (1) and (2) by the following modified relation [7]

$$q = \frac{1}{A_t} \Sigma \mu_\nu m_\nu H_\nu \tag{4}$$

in which $\underline{\mu_\nu}$ denotes a fraction between 0 and 1, giving the real degree of combustion for each individual component $\underline{\nu}$ of the fire load. The coefficient $\underline{\mu_\nu}$ then is a function of the type of the fuel, the geometrical properties of the fuel and the position of the fuel in the fire compartment, among other things. For some types of fire load components, the coefficient $\underline{\mu_\nu}$ will be dependent on the time of fire duration and on the gastemperature-time characteristics of the fire compartment.

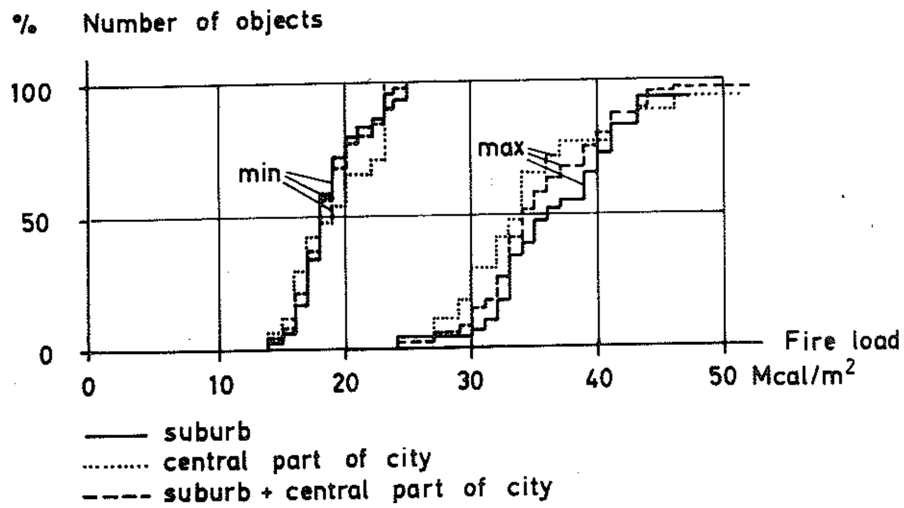


Figure 4. Distribution curves for the fire load $\underline{q}$, defined according to Eq. (2), representative to dwellings in the suburbs and the central parts of Stockholm [8]

A fragmentary example of a representation of fire load statistics in conformity with the idea of Eq. (4) is given in Fig 4 [8], which refers some distribution curves, representative to dwellings in the suburbs and the central parts of Stockholm. In the figure the fire load is specified on one hand by a minimum value, which only includes the highly inflammable components, and on the other hand by a maximum value, corresponding to all combustible material in the compartment, excluding floor covering. Within the European Convention for Structural Steelwork (CECM) probably a fire load representation will be chosen, which in some extent will take into account the real degree of combustion. For heavy components of the type book-cases then a fire load characterization will be applied with the degree of combustion dependent on the dispersion factor of the book-cases and on the fire duration, determined by the fire load for the rest.

With more distant aim, a further advanced development of the concept fire load seems to be unavoidable. One possible way then could be to specify the fire load according to Eq. (4) as well as the time variations of the rate of combustion and the emissivities of flames, glowing particles and combustion gases under well-defined conditions of combustion [3], [7].

2.2 FIRE GROWTH

The fire load of a compartment may be ignited from within the compartment or from adjacent fire compartments, if some relevant partition fails. Decisive factors for the process of ignition then are; cf Fig. 5 [1]:

- the characteristics of the source of energy,
- the type and the geometrical properties of the materials exposed, and
- the time of thermal exposure.

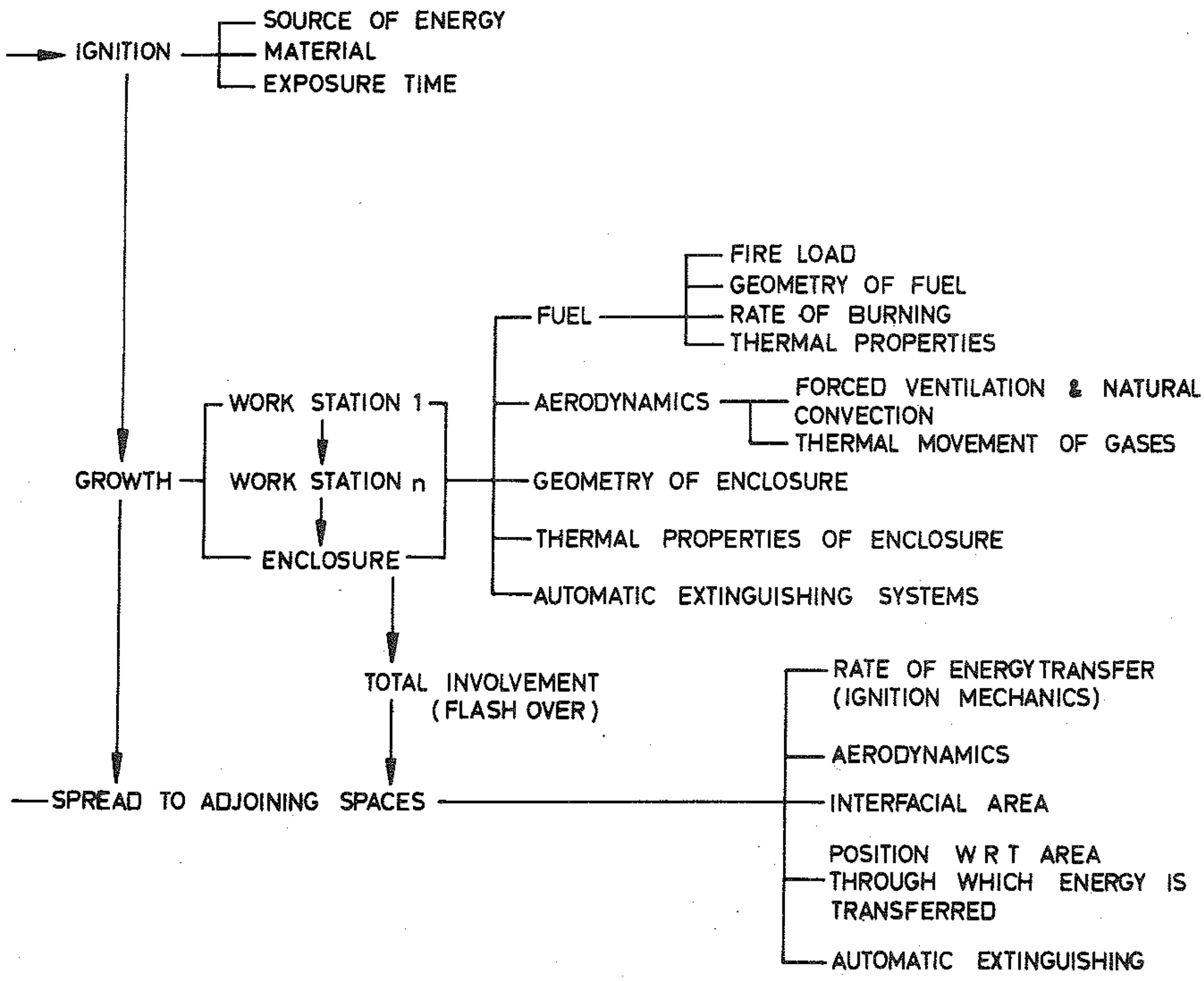


Figure 5. Factors affecting ignition, growth, and spread of fire in a building [1]

After ignition the fire begins to grow within the fire compartment at a rate which depends on the following main influences:

- the characteristics of the fuel (the fire load, the geometry of the fuel, its rate of burning, and its thermal properties),
- the aerodynamic conditions within the fire compartment (the forced ventilation, the natural convection, and the thermal movement of the gases due to fire),
- the geometry of the compartment,
- the thermal properties of the compartment, and
- the design and workability of an automatic extinguishing system, if any.

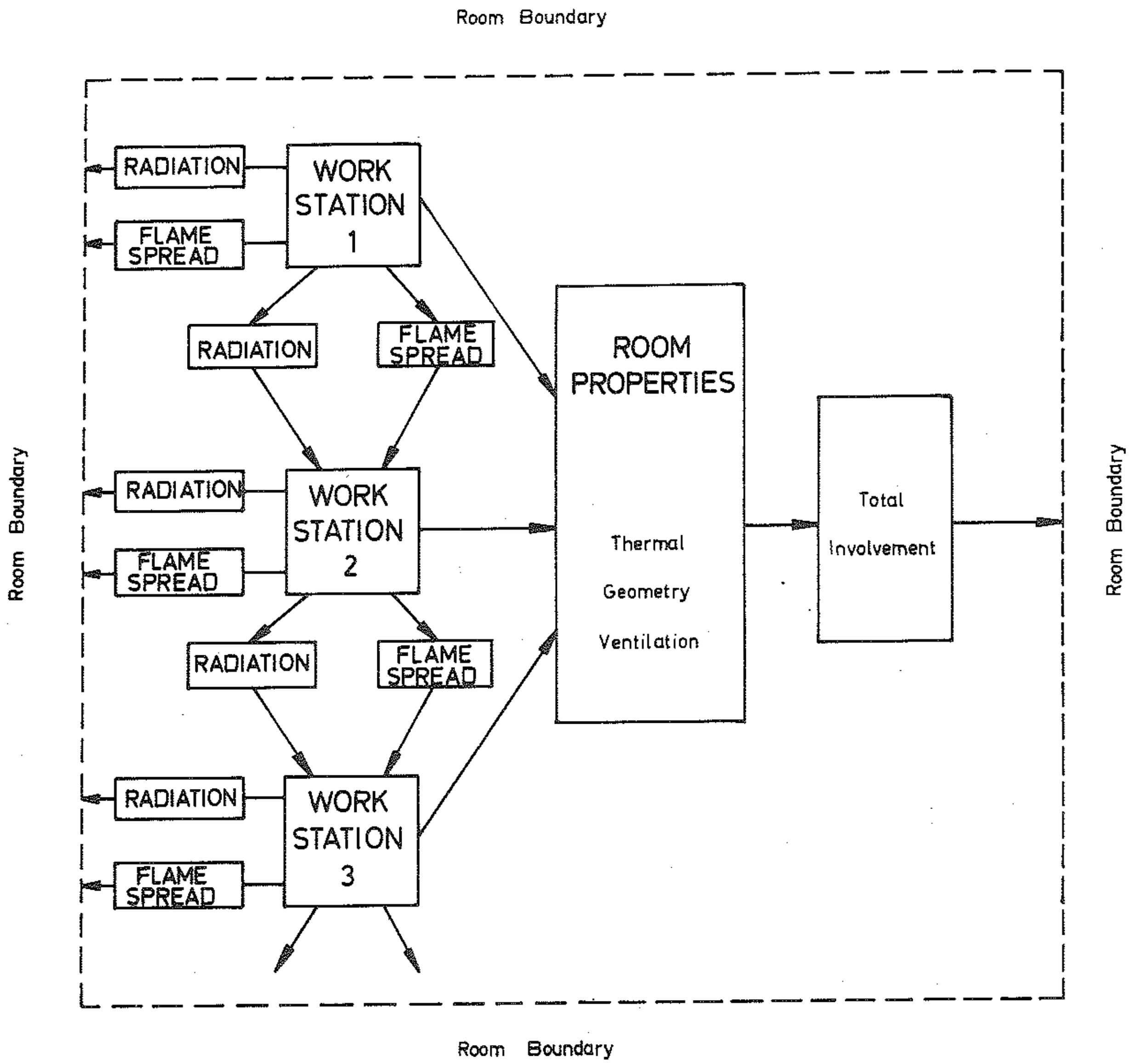


Figure 6. Model of the fire growth process within a compartment [1]

The fire growth takes place mainly by radiation and surface flame spread, slowly or rapidly leading to a total compartment involvement (flashover), if the fire does not extinguish itself or will be stopped by an automatic extinguishment system. A simple model, which illustrates this fire growth process, is given in Fig. 6 [1], showing the successive fire propagation from work station to work station within the compartment. A work station then is defined as a habitable area, usually associated with an activity and related to a cluster of potential fuel, i.e. a furniture grouping or a storage rack. For compartments with low values of the effective fire load - either a low fire load or a large fire load with decisive components with small fractions μ_ν - this fire propagation from work station to work station may occur without giving rise to any flashover within the compartment.

If the partitions, surrounding the compartment with the fire origin, do not fulfil their fire separating function, the fire will propagate to adjoining compartments. This fire spread from the room of origin is mainly influenced by (cf. Fig. 5):

- the rate of energy transfer,
- the aerodynamic conditions of the building,
- the interfacial areas between the room of origin and the adjoining rooms,
- the position of the receiving fuel element with respect to the area through which energy is transferred, and
- the characteristics of automatic extinguishing systems, if any.

As mentioned in SOA Report No. 1, an international co-operative research programme is going on within the CIB concerning a detailed study of the early stages of fire spread in a compartment. The programme, in which eight laboratories are taking part, is designed to give informations on the effect on the fire spread of the following eight influences:

- the shape of the compartment,
- the ventilation (window opening) of the compartment,
- the position of the ignition source,
- the area of the ignition source,
- the fuel height,
- the bulk density of the fuel,
- the continuity of the fuel, and
- the lining materials of the walls of the compartment.

On the basis of a discussion, prepared by Heselden and Melinek, the results of the first phase of the research programme were presented and discussed at a CIB W14 meeting in Stockholm in May 1972. From this some preliminary conclusions can be drawn.

The time, at which flaming has spread over the top of all the fuel (wooden cribs), the flashover time, does not differ significantly between two different shapes of compartments tested. It depends only to a small extent on the ventilation of the compartment and the continuity of the fuel and to a much larger extent on the other influences listed above. The results of six tests with various lining materials seem to indicate a correlation for the flashover time with the thermal inertia and a flame spread index of the lining material. Tests carried out with compartments of two different sizes have shown, that the flashover time remains more constant at the larger scale if the fuel height is scaled in proportion, too. This effect of a scaling of the fire conditions, as concerns a prediction of the time of flashover, has been studied more comprehensively in [9].

2.3 MAIN CHARACTERISTICS OF FULLY DEVELOPED FIRES IN A COMPARTMENT [10]

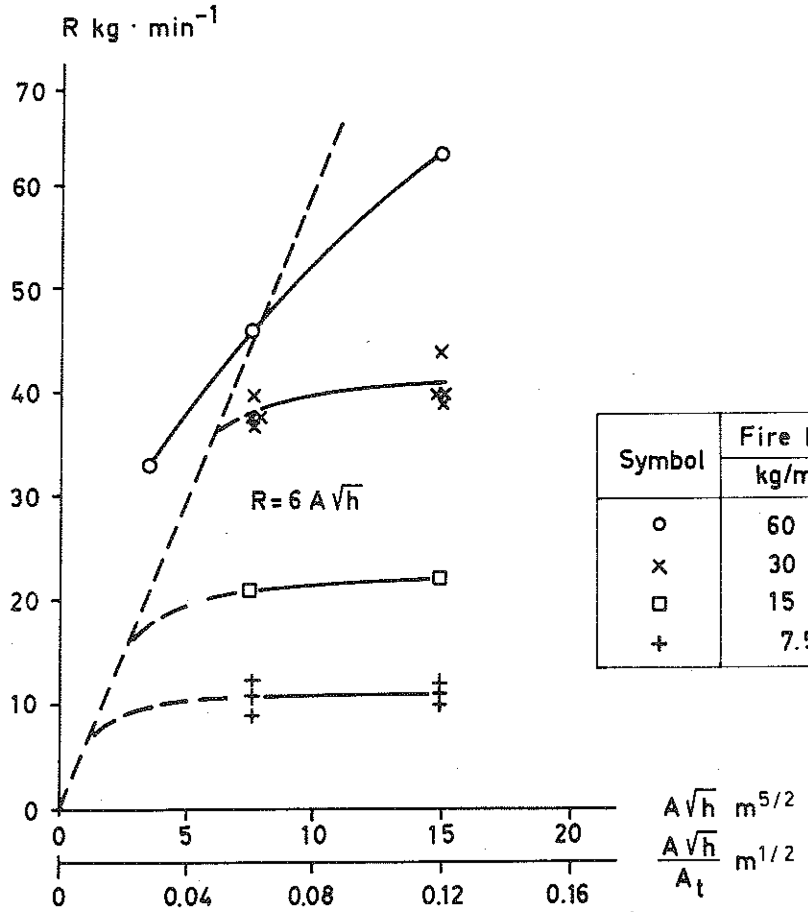
The most essential influences on the characteristics of a fully developed fire in a compartment are:

- the amount and type of combustible materials in the compartment (the fire load),
- the porosity and particle shape of the fire load,
- the distribution of the fire load in the compartment,
- the amount of air per unit time supplied to the compartment,
- the geometry of the compartment, and

- the thermal characteristics of the structures, enclosing the compartment.

In spite of a large number of important investigations, the present state of knowledge on the detail characteristics of compartment fires is far from satisfactory.

Simplified, fully developed compartment fires can be divided into two types of behaviour [11] . For the first type, the combustion during the flame phase is controlled by the ventilation of the compartment with the burning rate approximately proportional to the air supply through the openings of the compartment and not in any decisive way dependent on the amount, porosity and particle shape of the fuel. For the second type, the combustion during the flame phase is controlled by the properties of the fuel bed with the burning rate determined by the amount, porosity and particle shape of the fuel and largely independent of the air supply through the openings. The boundary between the two kinds of fire behaviour is not sharply marked.



Symbol	Fire load density	
	kg/m²	lb/ft²
o	60	12·4
×	30	6·2
□	15	3·1
+	7.5	1·55

Figure 7. Relation between average burning rate $\underline{R}$ (kg/min) and air flow factor $\underline{A\sqrt{h}}$ ($m^{5/2}$) or opening factor $\underline{A\sqrt{h}/A_t}$ ($m^{1/2}$) at varying fire load $\underline{q_c}$ (kg/m^2 floor area), determined for fully developed fires with piles of 4.5 cm wooden sticks in a compartment 7.7x3.7x3.0 m^3 [12] .

The phenomenon is illustrated more in detail by Fig. 7 and 8. Fig. 7 [12] then shows the experimentally determined relation between the average burning rate $\underline{R}$ and the air flow factor $\underline{A\sqrt{h}}$ or the opening factor $\underline{A\sqrt{h}/A_t}$ at varying fire load $\underline{q_c}$ for fully developed fires with piles of 4.5 cm wooden sticks. $\underline{A}$ = the total area of the window openings of the compartment, $\underline{h}$ = the height of the window openings, and $\underline{A}_t$ = = the total area of the surfaces bounding the compartment, openings included. The figure demonstrates clearly the two regions of ventilation controlled and fuel bed controlled fires with the burning rate $\underline{R}$ linearly dependent, respectively largely independent of the air flow factor or the opening factor. Fig. 8 [13], [14] complementarily demonstrates the same fact by showing the relation between the average gastemperature for the active part of a fire $\underline{\vartheta}_t$ and an inverse modified opening factor $\underline{A}_T/\underline{A}\sqrt{\underline{h}}$, received as a summary of the results of a comprehensive CIB co-operative study of fires in model compartments with fire load of piles of wooden sticks. In the figure, fuel bed controlled fires are to be found to the left and ventilation controlled fires to the right of the maximum point of the gastemperature $\underline{\vartheta}_t$.

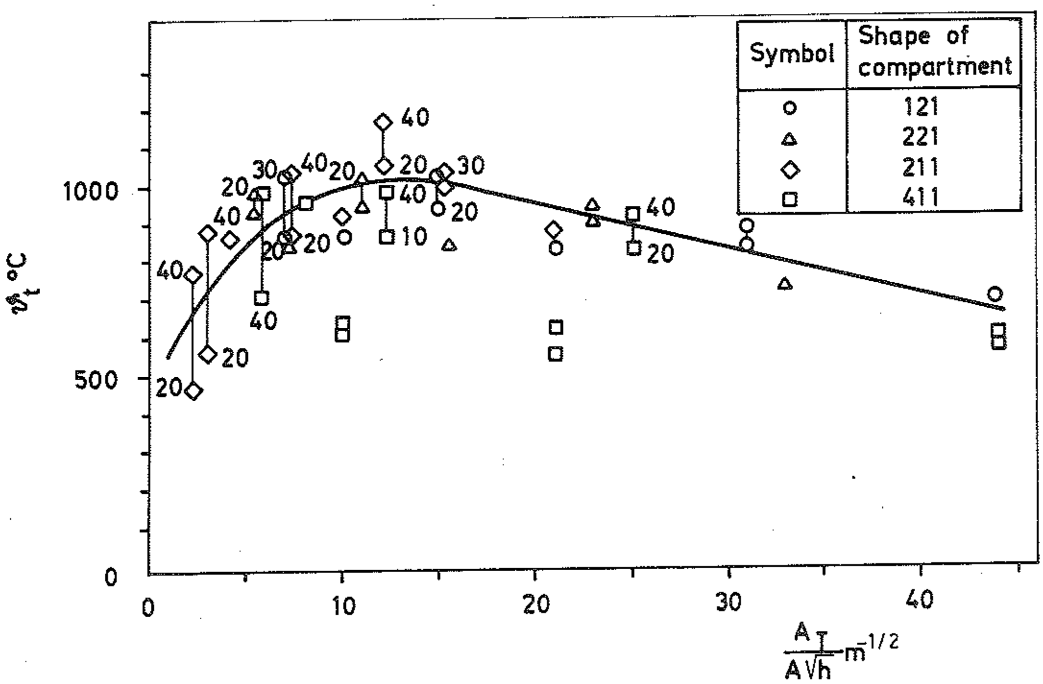


Figure 8. Relation between average gastemperature for the active part of a fire $\underline{\vartheta}_t$ and an inverse, modified opening factor $\underline{A}_T/\underline{A}\sqrt{\underline{h}}$, where $\underline{A}_T$ is the surrounding surface of the compartment, floor and opening areas excluded. Numbers represent fire load $\underline{q}_c$ in kg/m^2 floor area at ends of range of temperature. Summary of results of a comprehensive CIB co-operative programme on model scale studies of compartment fires with fuel of piles of wooden sticks [13], [14]

For ventilation controlled fires, we know from extensive experimental investigations at varying scales-summarized in [15] - that the average burning rate for the active part of a fire $\underline{R}$ approximately is related to the air flow factor $\underline{A}\sqrt{\underline{h}}$ by the relation

$$R = kA\sqrt{h} \qquad (5)$$

where $\underline{k}$ is a constant. For fire loads of piles or cribs of wood, fiber insulation board cribs and furniture, it is stated in [15] on the basis of experiments, carried out in Denmark, Japan, USA, UK and USSR, that the value of $\underline{k}$ is about 5.5 to 6.

$kg \cdot min^{-1} \cdot m^{-5/2}$, provided the area $\underline{A}$ is approximately one-quarter of the area of one side of the compartment, or less, and provided there is sufficient fuel for the burning rate of the fire to be ventilation controlled. At very small area $\underline{A}$ the coefficient $\underline{k}$ can increase to values of the level 9 to 10 $kg \cdot min^{-1} \cdot m^{-5/2}$.

Alternatively, Eq. (5) can be given in the following, dimensionless form [16]

$$R = 0.236\ \phi \tag{6}$$

where ϕ is a ventilation parameter of the same dimension as the burning rate $\underline{R}$ and defined by the relation

$$\phi = \rho_a \sqrt{g}\ A\sqrt{h} \tag{7}$$

ρ_a then is the density of air and $\underline{g}$ the acceleration due to gravity. With $\rho_a =$ $= 1.29\ kg/m^3$ and $\underline{g} = 9.8\ m/s^2$, Eq. (6) corresponds to the value 5.7 $kg \cdot min^{-1} \cdot m^{-5/2}$ of the constant $\underline{k}$ in Eq. (5).

Applying the ventilation parameter $\underline{\phi}$ and the initial free surface area of wood $\underline{A_s}$ as basic quantities, a plot of $\underline{R}/\underline{A_s}$ versus $\underline{\phi}/\underline{A_s}$ has been presented in [16] on the basis of results of full and model scale compartment burning tests available from numerous reports - Fig. 9. The results are connected to tests with fire loads of piles or cribs of wood.

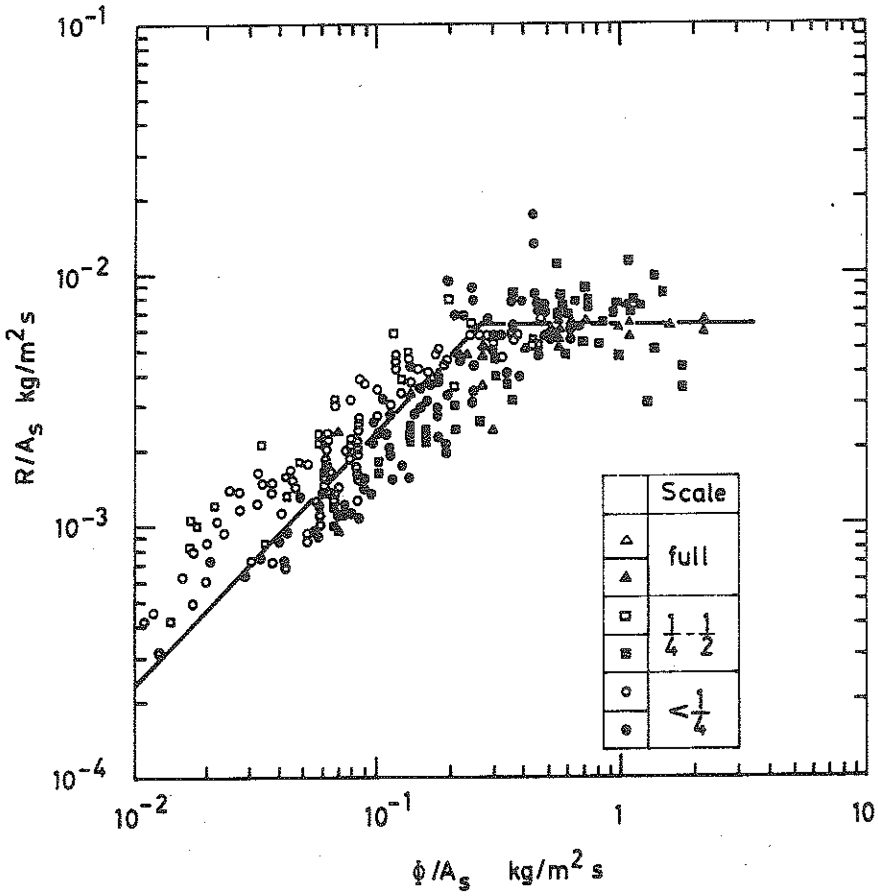


Figure 9. The ratio $\underline{R}/\underline{A_s}$ between average burning rate $\underline{R}$ and initial free surface area of the fire load $\underline{A_s}$ versus the ratio $\underline{\phi}/\underline{A_s}$ between ventilation parameter $\underline{\phi}$ and initial free surface area of the fire load $\underline{A_s}$, based on results of full and model scale compartment fires, available from the literature. Fire loads of wooden crib type [16]

The experimental data, given in Fig. 9, are characterized by a considerable scatter. In spite of this, two different regimes are recognizable, viz. the ventilation controlled regime, marked by an inclined line, and the fuel bed controlled regime, marked by a horizontal line. The lines correspond to Eq. (6) for ventilation controlled fires and to the relation

$$R = 0.0062 \, A_s \tag{8}$$

for fuel bed controlled fires. Eq. (8) then presupposes that $\underline{R}$ is given in kg/s and $\underline{A_s}$ in m^2. In Eq. (6) the constant is dimensionless.

According to Eqs. (6) and (8), the transition point between the two types of fire is determined by the value

$$\phi/A_s = 0.263 \ kg \cdot m^{-2} \cdot s^{-1} \tag{9}$$

for compartment fires with fuel of wooden cribs.

A principally similar characterization of compartment fires of wooden crib type has been deduced and presented in [17]. In this paper the transition between ventilation controlled and fuel bed controlled fires has been found to occur at the approximate value

$$\frac{M}{rA\sqrt{h}} = 17000 \ kg/m^{7/2} \tag{10}$$

where $\underline{M}$ is the total fire load in kg, and $\underline{r} = \underline{V}/\underline{A_s}$ expresses the ratio of the total volume $\underline{V}$ of the fuel and its initial free surface area, the hydraulic radius. With a presentation according to Fig. 9, the transition point given by Eq. (10) corresponds to a somewhat lower value of $\underline{\phi}/\underline{A_s}$ than the value determined by Eq. (9). As has been established above, there is no sharply marked boundary between the two kinds of fire behaviour in reality, but instead the ventilation controlled and fuel bed controlled fires are separated by a critical regime.

Going over from fuel of wooden crib type to more realistic fire loads of furniture, it can be stated summarily, that the average burning rate of the active part of the ventilation controlled fires still can be determined from Eq. (5) or (6) with an accuracy which is sufficient in most practical cases of a structural fire engineering design. For fuel bed controlled fires, considerable difficulties are added, primarily in defining a representative free surface area $\underline{A_s}$ or hydraulic radius $\underline{r}$ of a furniture fire load from a combustion point of view. Furthermore, some full scale tests of compartment fires with fire loads of furniture, representative for dwellings seem to indicate a not inconsiderable displacement of the transition point or regime between ventilation controlled and fuel bed controlled fires in the direction of a larger value of $\underline{\phi}/\underline{A_s}$ or a smaller value of $\underline{M}/\underline{rA\sqrt{h}}$ [17], [18]. At present, the only way to take into account in a practical fire engineering design the specific, favourable characteristics of a fuel bed controlled fire will be to calibrate at first the real furniture fire load in a full scale test. With regard to the large scatter of the fire load properties for each single type of compartment in practice-accentuated in an international comparison - such a calibration procedure ordinarily will require very extensive series of full scale fire tests with authentic fire loads, chosen with the probabilistic characteristics taken into consideration.

Future research activities for a combined experimental and theoretical explanation of the detail characteristics of the fuel bed controlled compartment fires are evidently of high priority. Systematic, extensive studies on this subject also are in progress; cf. for instance [19].

2.4 THEORETICAL DETERMINATION OF GASTEMPERATURE-TIME CURVE OF FULLY DEVELOPED FIRES IN A COMPARTMENT

At known input data, a calculation of the gastemperature-time curve (ϑ_t-t) of the complete process of fire development in a compartment can be carried out in the single case over the heat balance and mass balance equations of the fire room. Such a calculation is based on the identity between released quantity of heat and removed quantity of heat per unit time, i.e.

$$I_C = I_L+I_W+I_R+I_B \tag{11}$$

where

I_C = quantity of heat released per unit time from the combustion of the fuel,
I_L = quantity of heat removed from the compartment per unit time by change of hot gases against cold air,
I_W = quantity of heat transferred to the surrounding wall, floor and roof structures of the compartment per unit time,
I_R = quantity of heat radiated through the openings of the compartment per unit time, and
I_B = quantity of heat stored per unit time in the gas volume of the compartment - ordinarily negligible.

A systematized method of calculation, based on Eq. (11), was developed near simultaneously by Kawagoe-Sekine [20] and Ödeen [21]. The problem is dealt with on the simplified assumptions that the temperature in the whole compartment is uniform at any moment, that the coefficients of heat transfer at the internal surfaces bounding the compartment are equal at all points, that the heat flow through the wall, floor, and roof structures enclosing the compartment is one-dimensional, and that this heat flow is uniformly distributed, abstracting from window and door openings.

The method of calculation, deduced by Kawagoe-Sekine and Ödeen is restricted in application to the flame or heating period of the process of fire development, as concerns fire loads of the type, representative to building compartments in practice. A generalized method, which makes possible a calculation of the gastemperature-time curve for the complete process of fire development, has been put forward later on by Magnusson-Thelandersson [17], [22]. The design procedure contains a computer programme, which enables a consideration of temperature dependant thermal properties and critical temperatures for decomposition of the materials entering into the surrounding structures, initial moisture content in the surrounding structures, effect of heat stored in structures enclosed in the compartment, and changes in size and shape of window and door openings during the process of fire development. The procedure is applicable to compartments, which contain up to three different types of surrounding structures with one of these structures composed of up to three different materials.

A practical application of the design procedure presupposes that the time variation of the combustion rate, specified as the quantity of released heat per unit of time, is known. Such a variation can easily be given for well-defined fuels without any smoulder phase. The procedure has also been applied successfully in analysing the results of compartment fire tests with fuels of this type [23]. For not well-defined fuels - for instance fire loads of wooden type - a determination of the time-variation of the amount of the released heat per unit of time during a complete fire process is connected to great experimental difficulties. Further developments of laboratory test methods for a small scale determination of the rate of heat release of materials and linings at accurately specified heating conditions, recently published then could be a future way of solving this problem, cf. e.g. [24], [25]. At present essential, necessary informations are lacking concerning such fundamental problems as a transformation of the burning rate expressed as weight loss per unit of time $\underline{R}$ to a burning rate given as the quantity of released heat per unit of time $\underline{I}_C$ or a division of the total amount of the released heat during a fire to the flame and cooling periods.

With the goal of deriving gastemperature-time curves for the complete process of compartment fires, which can be used as a provisional basis for a differentiated structural fire engineering design, giving values of the fire resistance of structures, which are not unsafe, the problems summarized above have been tackled in [17] , [22] in the following way.

From the discussion carried through in chapter 2.3, some general conclusions can be drawn of basic interest in this connection. For ventilation controlled fires, the burning rate of the active part of the fire can be determined from Eq. (5) or (6) for different types of fire loads, furniture included, with an accuracy which is sufficient in most practical cases of a structural fire engineering design. For fuel bed controlled fires, the present state of knowledge is too incomplete for enabling a satisfactory corresponding calculation of the burning rate in practice with the fire load consisting of furniture, very difficult to define with regard to a representative free surface area $\underline{A}_s$ or hydraulic radius $\underline{r}$. In such a position it seems reasonable to base a differentiated structural fire engineering design on characteristics for the process of fire development which constantly have been determined on the assumption of the fire to be 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.

With this philosophy applied, in [17] , [22] are analysed such full scale experiments with wood fuel fires in compartments which have been reported in the literature in a sufficiently accurate manner. For each individual experiments, then a theoretical determination has been carried through of that time curve for the released quantity of heat per unit of time, which gives the best agreement for the complete process of fire development between the theoretically calculated and experimentally determined gastemperature-time curves for the compartment. An example from this analysis is given in Fig. 10 [17] , showing a comparison between measured (dash-line curve) and computed (full-line curve) gastemperature-time curves for a full scale test, characterized by a fire load $\underline{q}_c$ = 60 kg/m^2 floor area and an opening factor $\underline{A\sqrt{h}/A_t}$ = 0.06 m$^{1/2}$. $\underline{A}_t$ = the total surrounding area of the compartment, floor and opening areas included. In the figure also are shown the corresponding computed time curves for the terms $\underline{I}_C$, $\underline{I}_L$, $\underline{I}_W$, and $\underline{I}_R$ of Eq. (11). Generally, the experiments have been analysed with the condition

$$WM = \int_0^\infty I_C \, dt \qquad (12)$$

always fulfilled. $\underline{M}$ = the total fire load, $\underline{W}$ = the heat value of fuel per unit weight, and $\underline{t}$ = the time coordinate. This means, that the total fire exposure of a structure or structural element always will be the same for a given fire load, independent of how the heat release per unit of time $\underline{I}_C$ varies with the time $\underline{t}$.

The results from calculations of the described type have enabled a construction of representative, simplified time curves for the quantity of released heat per unit of time under varying presumptions. On the basis of these time curves then very extensive calculations have been carried out in a systematic way of the gastemperature-time curve of the complete process of fire development for varying assumptions concerning the geometrical and thermal characteristics of the room, the opening factor $\underline{A\sqrt{h}/A_t}$ and the fire load $\underline{q}$, defined as the corresponding heat value per unit area of the total surface bounding the fire room. As a fragmentary illustration of the results presented, Fig. 11 reproduces theoretically determined gastemperature-time curves $\underline{\vartheta_t}$-$\underline{t}$ at varying fire load $\underline{q}$ and opening factor $\underline{A\sqrt{h}/A_t}$ for a compartment with surrounding structures, 20 cm in thickness and made of a material with a thermal

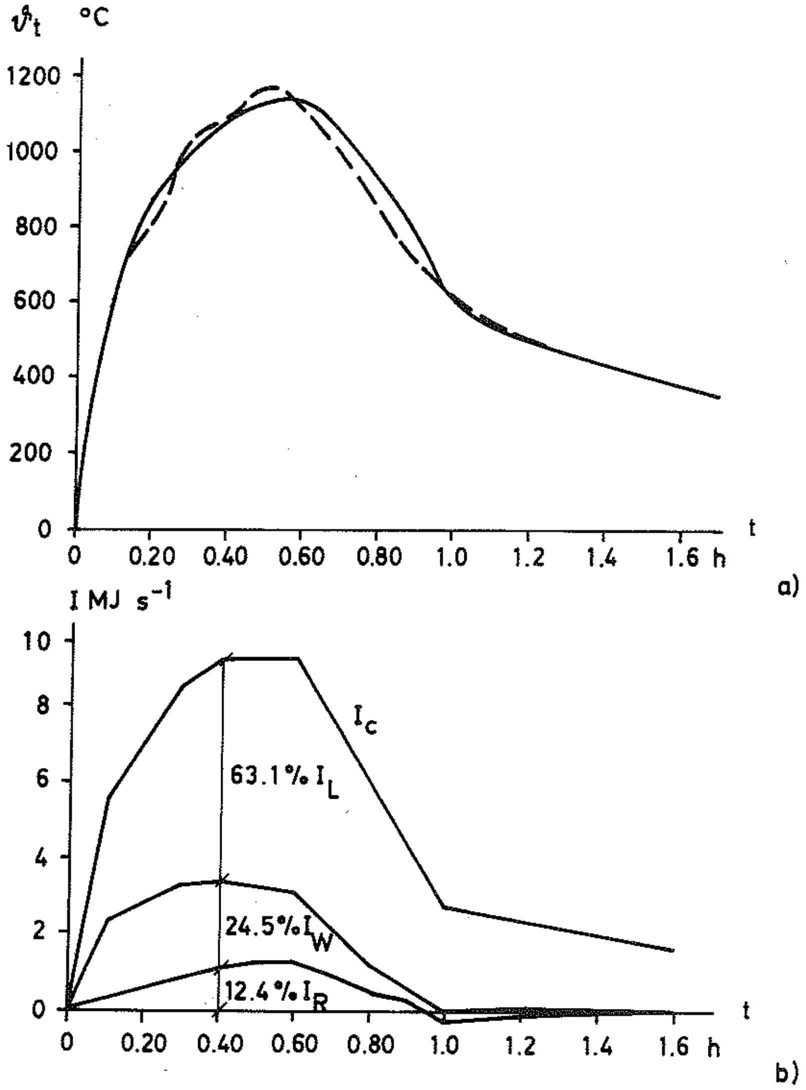


Figure 10. a) Measured (dash-line curve) and computed (full-line curve) gas-temperature-time curves for a full-scale test, carried out at Fire Research Station, Boreham Wood, and characterized by a fire load $\underline{q}_c$ = $= 60$ kg/m^2 floor area and an opening factor $\underline{A}\sqrt{\underline{h}}/\underline{A}_t = 0.06$ m$^{1/2}$
b) Computed corresponding time curves for $\underline{I}_C$, $\underline{I}_L$, $\underline{I}_W$, and $\underline{I}_R$ in Eq. (11) [17]

conductivity $\underline{\lambda} = 0.7$ kcal·m^{-1}·h^{-1}·°C^{-1} and a heat capacity $\underline{\gamma c}_p = 400$ kcal·m^{-3}·°C^{-1} as representative average values within the temperature range associated with fires.

It is important to stress that the gastemperature-time curves, published in [22] and exemplified in Fig. 11, generally have been determined on the assumption of ventilation controlled fires. As a consequence, the curves are not intended to be used directly for theoretical comparisons with experimentally received results from wooden crib compartment fires of strongly marked fuel bed controlled type. In such a connection, the method of calculation according to [17], [22] of course is to be based on Eq. (8) for the rate of combustion. The agreement between the theoretical and experimental results then will be satisfactory, too. One principal reason for choosing ventilation controlled fire characteristics as a general assumption for the determination of the gastemperature-time curves according to

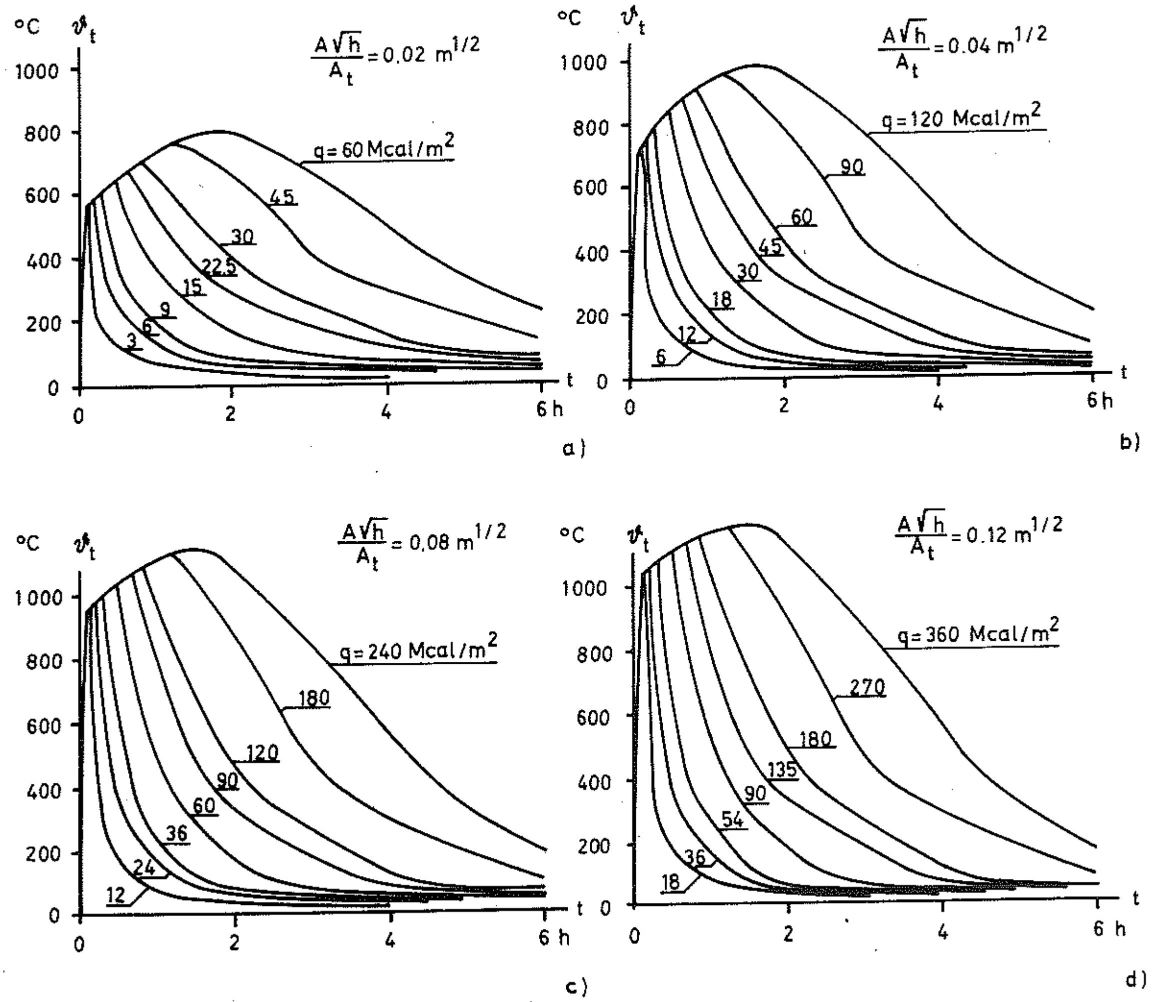


Figure 11. Gastemperature-time curves (ϑ_t-t) of the complete process of fire development for different values of the opening factor $A\sqrt{h}/A_t$ ($m^{1/2}$) and the fire load q ($Mcal/m^2$ of the total surface bounding the compartment). The curves correspond to a wood fire burning in a room enclosed by structures, 20 cm in thickness and made of a material with a thermal conductivity λ = = 0.7 kcal/m·h·°C and a heat capacity γc_p = 400 kcal/m³°C as representative average values within the temperature range actual [22]

[22] , is dictated by the great difficulties to find a representative value of the free surface area or the hydraulic radius of a real fire load of furniture for a combustion description of a fuel bed controlled fire. Another principal reason is connected to the fact that the gastemperature-time curves themselves do not constitute the primary interest of the problem but an intermediate part of a determination of the decisive quantity, viz. the minimum value of the load-bearing capacity of a fire exposed structure during a complete process of fire development. For fuel bed controlled fires, the assumption of ventilation control in combination with the fulfilment of the condition, given by Eq. (12), leads to a structural fire engineering design which will be on the safe side in practically every case, giving an overestimation of the maximum gastemperature level and a simultaneous, partly balancing underestimation of the time of fire duration. For the minimum load-bearing

capacity or the fire resistance time, the gastemperature-time curves according to [22] give reasonably correct results, which has been verified fragmentarily in [26] and also in other applications.

In combination with rules for a transformation of gastemperature-time characteristics for a compartment with given thermal properties of the surrounding structures to the gastemperature-time curves according to Fig. 11 - for instance, via fictitious values of the fire load $\underline{q}$ and the opening factor $\underline{A}\sqrt{\underline{h}}/\underline{A_t}$ - these latter curves therefore can be used as a temporary basis for a differentiated structural fire engineering design.

2.5 FIRE SPREAD ALONG AN OUTER WALL OF A MULTISTOREY BUILDING

For a safe judgement of the risk of exterior vertical window-to-window fire spread in a high-rise building, systematized informations are requisite concerning the thermal characteristics in front of the outer wall during a fire in one distinct storey of the building. Such informations are necessary also for a structural fire engineering design of, for instance, exterior load-bearing columns.

The problem contains a large number of variables, viz. for the fire compartment:

- the amount and type of the fire load,
- the porosity and particle shape of the fire load,
- the distribution of the fire load in the compartment,
- the geometry of the compartment,
- the size and shape of the windows,
- the thermal properties of the structures, enclosing the compartment, and
- the detailed structural design in connection with the window openings,

and for the outer wall:

- the properties of the facade materials with respect to combustibility,
- the emissivity of the facade, and
- the thermal inertia of the surface layer of the facade.

In spite of important contributions to the problem in Japan, UK, and USA - cf. for instance [27] - [29] - the present state of knowledge is unsatisfactory as a basis for a differentiated fire engineering design. As a consequence, continued, combined experimental and theoretical research on the problem must be called for with the intention to develop a general method of calculation for a determination of the decisive detail temperature and radiation exposure on a facade at a fire in a distinct storey of a multistorey building. Several of the influences, enumerated above, then are characterized by a considerably stronger importance than for the properties of the fire development in a compartment - e.g. the amount and distribution of the fire load, flammable linings and carpets.

In Fig. 12 the problem is spotlighted by a series of experimentally determined temperature fields outside of the outer wall of a model test building at four different processes of fire development in the fire compartment, characterized by the respective opening factor values $\underline{A}\sqrt{\underline{h}}/\underline{A_t}$ = 0.015, 0.026, 0.038, and 0.075 $m^{1/2}$ at a fire load $\underline{q}$ = 19.6 $Mcal/m^2$ of the total surface bounding the compartment [30]. The temperature fields shown correspond to a vertical symmetrical section at right angles to the wall and to the time for maximum gastemperature in the fire compartment.

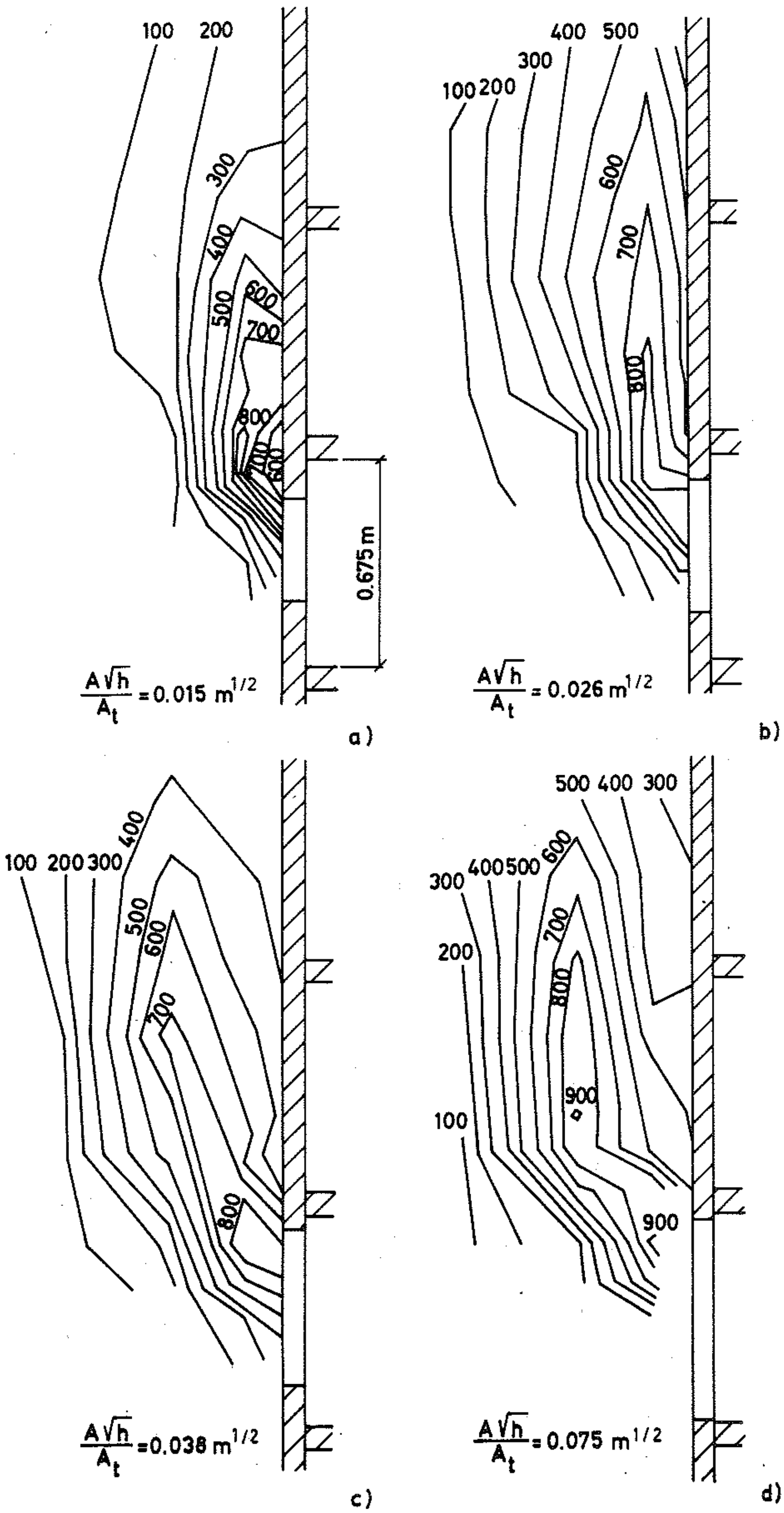


Figure 12. Temperature fields outside of the outer wall of a model test building, determined in a vertical symmetrical section at right angles to the wall and corresponding to the time for maximum gastemperature in the fire compartment. Model scale 1:4. Fire load q = 19.6 Mcal/m^2 surrounding surface. Opening factor $A\sqrt{h}/A_t$ = 0.015 (Fig. a), 0.026 (Fig. b), 0.038 (Fig. c), and 0.075 m$^{1/2}$ (Fig. d)

2.6 GENERATION AND MOVEMENT OF SMOKE AND COMBUSTION GASES [1]

In any building fire, hazardous pyrolysis and combustion products are generated, consisting of a mixture of irritating, toxic or corrosive gases - e.g. CO, HCN, $COCl_2$, HCl - with a structure which depends on the characteristics of the fuel and the degree of combustion. In addition, the combustion products consist of visible smoke, i.e. particulate matter and dispersed liquids suspended in air - principally unburned carbon resulting from incomplete combustion [31] . The visible particulate matter, unburned carbon and tars, generally is not considered toxic. However, smoke may contain strong irritants or lachrymators, which can affect the eyes and nasal passages and result in reduced vision, coughing, extreme discomfort, or pain and may lead to panic. In high concentration, obscuration by smoke hinders the evacuation procedures, life rescue operations and fire fighting. Inhaled in large doses smoke may cause physiological lung damage.

The pyrolysis and combustion products are ordinarily not bounded to the compartment of fire origin but dispersed with normal or fire-generated air currents to other sections of the building thus posing a life hazard also to occupants who are remote from the fire. The phenomenon was dramatically illustrated by a fire in New York a couple of years ago; there the smoke generated in a fire in the basement of a tall building caused the death of two firemen on the 22nd floor where no fire occurred [32] . Because even a small fire can generate considerable volumes of smoke and threaten the occupants within large sections of the building, it is absolutely necessary that the smoke movement is restricted and controlled for enabling smoke safe areas of refuge and ways out of and into the fire floor.

In a tall building, the hazard potential from the combustion products of a fire is greatly magnified primarily for the following reasons:

- the presence of large quantities of electrical wire insulation and thermal insulation materials may increase the fire load and the corresponding potential for hazardous smoke and gas generation,
- the frequent use of fire retardant structural and finish materials causes an increased probability of generating toxic products of decomposition from the flame inhibiting chemicals,
- the large number of ventilation, airconditioning and service ducts, elevator shafts and stairwells contribute to a greater risk of spread of the combustion products, and
- a larger number of people may be exposed to toxic gases for a longer period of time as a consequence of a longer evacuation time for a tall building than for a low building.

For a <u>classification of materials</u> with regard to their smoke generation capabilities, a relatively large number of laboratory standard test methods have been developed. In the methods, generally the light obscuration of the resulting smoke is measured, when a specified surface area of the material is exposed according to a precisely defined heating technique. An excellent survey of some of the existing test methods for smoke measurement is given in [31] , including a summary, comparative examination of the methods with respect to reproducibility and repeatability, relation to hazard in building fires, and size and cost of apparatus.

The test methods usually give the results in such a way that a classifying of a product in a range is possible. As an example, the characteristics of the ASTM E84 Tunnel test in this respect may be mentioned [31] , [33] . The primary purpose of the test is a determination of a surface flame spread rating, but the test also involves measurements of the heat developed through a fuel contributed factor and the smoke developed through a smoke density factor. Asbestos-cement board is used as one calibration material and red oak flooring as the other. When exposed to standard fire conditions, the asbestos-cement board is given a zero rating for flame spread, fuel contributed, and smoke density; similarly, red oak flooring is given a 100 rating for these three items. Test results for all other materials are compared to these ratings. This standard test has been adopted widely in US building codes for the control of flammability of interior finishes and as a control on smoke density.

Laboratory test methods have also been developed for a determination of the gaseous pyrolysis and combustion products of materials in fire. In these methods, generally a small sample of the material is heated in a specific manner under an inert or oxidizing atmosphere and the gaseous products are analysed by mass spectrometry or gas chromatography.

Going from a characterization of materials according to laboratory test results for type and concentration of generated gases and smoke to a practical prediction of the hazard potential of an enclosure, it can introductory be stated, that the density of smoke and the gaseous pyrolysis and combustion products in an area of a building will depend on [1], [31]

- the material burning or exposed to sufficient heat to cause decomposition,
- the amount of surface area involved,
- the rate of heating,
- the temperature level,
- the volume of the space, in which the smoke and the pyrolysis and combustion products are dispersed,
- the diffusion within that space, and
- the amount of ventilation provided.

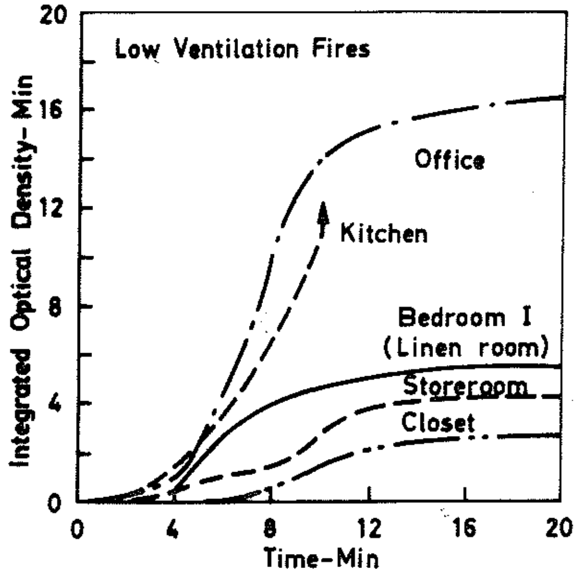
In real building fires, the time variations of these influences can be considerable and, as a consequence, a precise prediction of the levels of smoke and pyrolysis and combustion gases to be expected in any particular fire always will be impossible.

As concerns smoke, the ability of small-scale tests to predict full-scale smoke production recently has been examined on the basis of comparative tests in [34]. From the conclusions given in this paper, the following may be extracted as an example of the discussion going on.

No single smoke rating number should be expected to define relative smoke hazards of material in all situations. For the materials studied in the test series reported, it appears that the ASTM E84 Tunnel test data modfied to give smoke developed in terms of integrated optical density may provide a useful measurement of smoke produced by interior finish materials in a corridor along which an exposing fire spread. None of the small-scale test methods examined adequately correlated with the smoke produced by finish materials totally involved in a fully developed full-scale compartment fire. The inadequacies of the test methods in this respect seem to be concerned with their inability to produce the extremely heavy smoke associated with total involvement of some materials, particularly those of higher fuel content. Consequently, it seems reasonable for the future to try to develop a small-scale test procedure, giving a judicious combination of results from tests under two or more widely differing exposures and providing the basis for a rating system that adequately accounts for the effects of material location, fire intensity, and other relevant factors for materials completely involved in a compartment fire.

Complementary, it is stated in [31], that perhaps the greatest need at the moment, as concerns future research work on smoke in building fires, is for large-scale tests through which the true hazard of smoke and meaningful end points can be defined. Such research work also is in progress at various laboratories over the world. A fragmentary example of test results received is given in Fig. 13 [35], showing the relative smoke production in six low ventilation fires, representative to six different types of occupancy. Research work of this kind may disclose the significance of smoke as a life safety factor in the initially developing fire as against the fully developed fire. In this respect, the situation may be quite different in buildings of varying size and height.

As concerns combustion gases in building fires, there are at present no standard tests that may be used to rate the potential of a material for toxic gas generation.



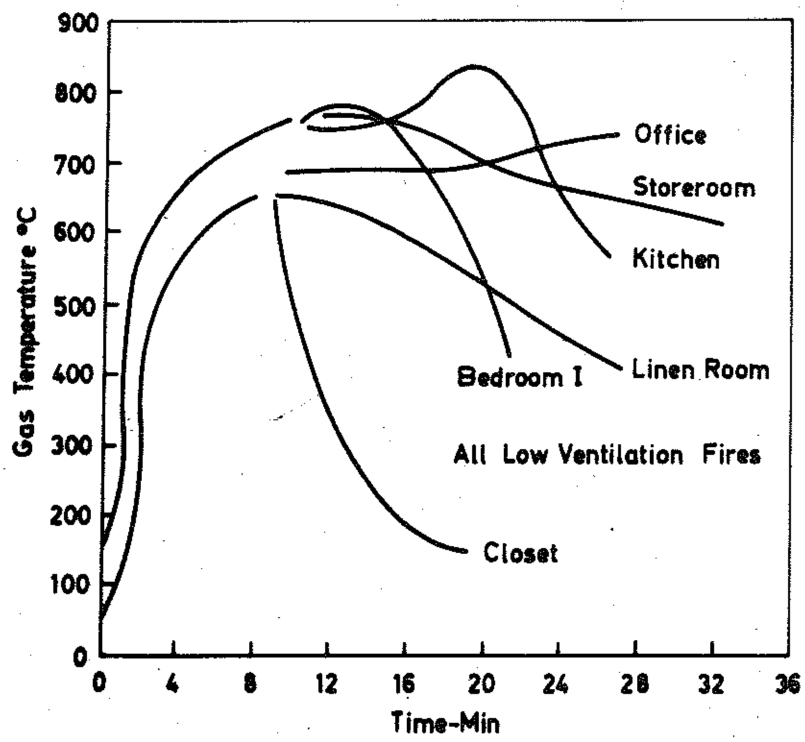


Figure 13. a) Integrated optical densities of smoke for six low ventilation full-scale compartment fires as functions of time. The different curves refer to various types of occupancy with representative fire load characteristics b) The corresponding time curves of gastemperature at ceiling of fire compartment [35]

The development of such a standard test probably will be a greatly complicated research work, but feasible and necessary. One strongly complicating factor then is the difficulty in defining the toxic level of a mixture of gases because of observed synergistic effects between gases. Parallel to a development of a standard test procedure for toxic gas generation, it is urgent, too, to develop a model of analysis for predicting the toxic hazard potential of a given compartment containing a multiplicity of materials.

As indicated earlier, a differentiated knowledge on the characteristics of the movement of smoke and hazardous gaseous products in connection with a building fire is of great importance for a choice of adequite measures, for instance in making escape routes and areas of refuge safe.

With regard to movement, smoky and normal atmospheres are virtually indistinguishable. The principal constituent of both is nitrogen, and although the oxygen and carbon dioxide contents may differ by about 10 per cent, this will not substantially affect the physical properties of the atmosphere. The properties of the particulate smoke component differ markedly from those of, say, nitrogen; but the concentration will not be sufficient to influence the over-all movement of the atmosphere even at levels that reduce visibility to virtually zero [36].

Usually, the temperature differentials and variations are the most important factors for the smoke movement mechanism. Additional factors are pressure differentials associated with winds, blowers, fans, and mechanical ventilation systems. In the immediate area of the fire, a continuous temperature increase causes the expansion displacing the greater proportion of the volume of the gases involved. Simultaneously, the chimney or stack effect proceeds continuously whenever there is any temperature differential between interior and exterior. During a fire, then ordinarily the chimney effect dominates over the thermal expansion effect. The chimney effect is also responsible for much of the normal air movement in buildings, as usually some level of temperature differential exists between a building and the exterior atmosphere. Since the temperature of smoke-laden gas can decrease rapidly at any distance from the fire, in a tall building the normal air movement will be largely responsible for the widespread distribution of smoke.

The movement of smoke at a fire in a high-rise building can be analytically modelled and solved by computer techniques, cf. [36] - [39]. The computer procedure can be characterized by the following steps of calculation [39]:

(1) the calculation of the pressure distribution in vertical shaft of the building,
(2) the calculation of the mass rates of inflowing air and outflowing smoke in the fire compartment and of the pressure differentials at the openings between the fire compartment and staircases and ducts,
(3) the calculation of the mass rates of air at each opening of the building,
(4) the correction of the first approximation solution according to (1) to (3) by means of the mass balances in staircases and ducts,
(5) the calculation of the safety time for escape, using the results in (4), and
(6) an eventual, complementary calculation of the influence of an air supply or a smoke exhaust for the staircases.

A theoretical study of the type described makes possible the following predictions [38]:

- the smoke concentration as a function of time and location within the building, if the smoke concentration characteristics for the fire compartment are known,
- the air flow quantities through all flow paths examined,
- the pressure in all spaces examined,
- the pressure differentials across doors (establishing forces necessary to open doors),
- the pressure differentials across exterior walls and windows, plus certain critical

interior walls, and
- the infiltration and exfiltration through exterior walls.

Results, useful for a functional discussion of the smoke movement mechanism and for a determination of suitable measures with respect to smoke control, are presented in [36] - [40] and in SOA Report No. 5. In this latter report also is referred a flow diagram for an over-all smoke protection design system according to Wakamatsu.

3. SOME SPECIFIC FIRE ENGINEERING DESIGN PROBLEMS IN HIGH-RISE BUILDINGS

In this chapter, some general points of view and characteristics will be given on some specific fire engineering design problems in tall buildings. The problems to be dealt with are:

- occupant protection,
- personnel movement,
- life support systems,
- emergency communications and controls,
- structural integrity, and
- fire-fighting appliances and conveniences.

The treatment mainly will be based on the findings and recommendations, resulting from the GSA international conference on firesafety in high-rise buildings, held at Airlie House, Warrenton, April 12 - 16, 1971 and from the subsequent reconvened conference, held in Washington, October 5, 1971 [1], [41]. For more detailed remarks, reference can be made to SOA Report No. 2, as concerns structural systems, and to SOA Reports No. 3 and 4, as concerns the other subjects listed above. In this connection, reference also should be given to [42], in which an extensive list of recommendations is presented, originating from the knowledge received in connection with the fire at One New York Plaza in 1970.

The primary base for the development of all fire reacting systems, equipment, and elements is the factor, representing a designed limitation of the potential of the maximum expected fire. Basically, there are three methods for a fire potential limitation, viz. fuel control, compartmentation, and automatic extinguishing.

A control of the potential fuel for fire comprises both the direct combustion potential and the potential for the development of smoke and toxic gases. At present, such a control can be performed by code regulations and construction contract requirements, as concerns building materials, while it is almost impossible to prescribe any significant limitations on the building occupancies. Simplified, it can be summarized that the policing of a fuel-limited design is an important problem but basically connected to great practical difficulties.

Compartmentation constitutes an essential design measure for limiting the size of a fire. Compartmentation then means a dividing of the building into limited, protected areas which will allow the fuel to burn out without any fire spread beyond the compartment location. The complete success of a compartmentation requires that the barriers and partitions are able to fulfil their functions with respect to integrity and insulation during the whole process of fire development. The probability of success of a barrier decreases with an increased degree of incompleteness of the barrier. This particular problem is illustrated by Fig. 14 [41], showing expected probability of functional fulfilment for four different types of barriers, plotted against the percentage portion of the barrier involved in openings or other elements of incompleteness.

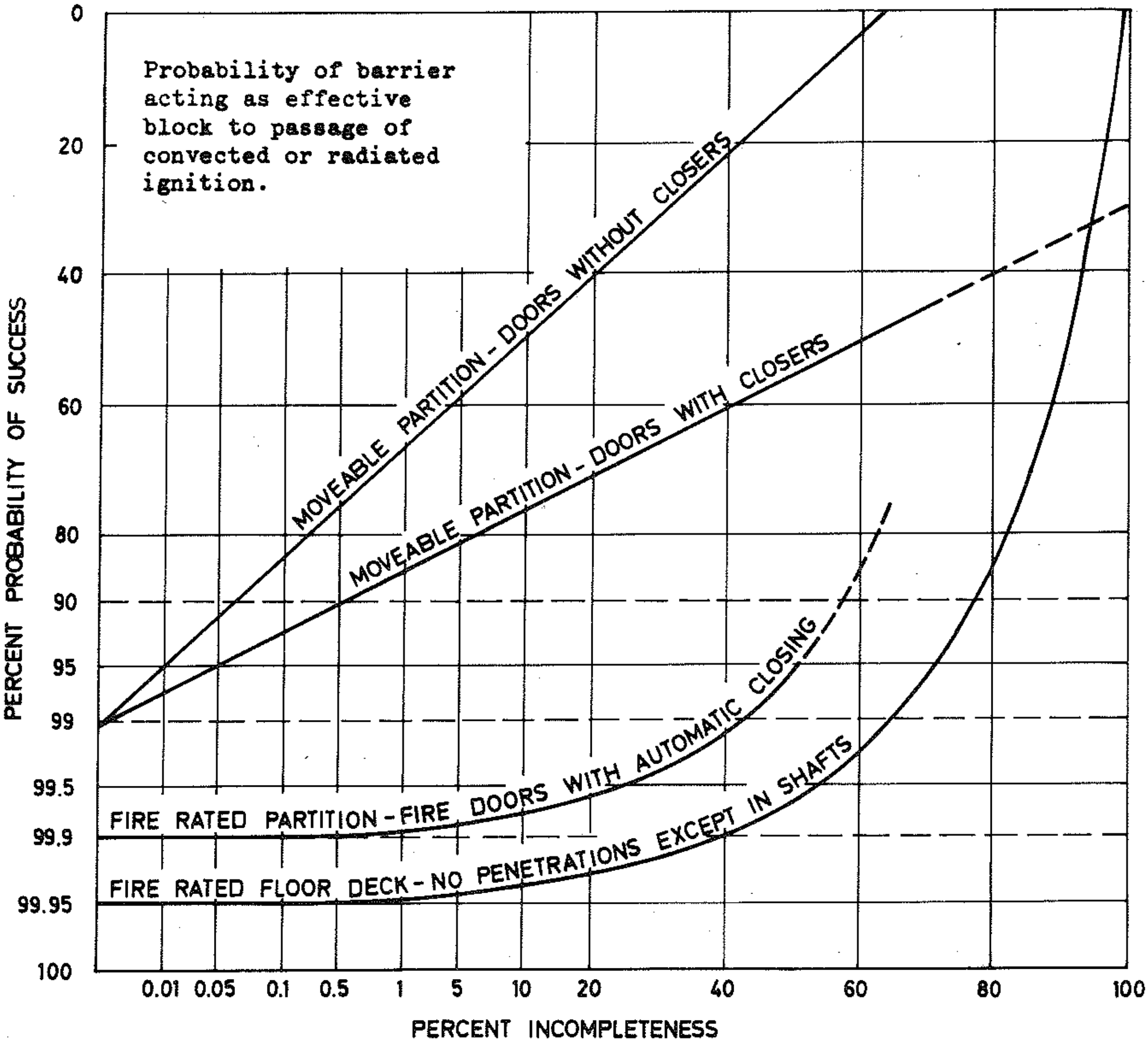


Figure 14. Percent probability of success for four types of barriers or partitions as function of percentage degree of incompleteness of the elements [41]

The third method for a fire potential limitation, automatic fire extinguishment systems such as the automatic sprinkler system, probably gives the most flexibility and least restraint to the design, use, and operation of tall buildings. Automatic extinguishing systems are designed to deliver extinguishing agents directly into the fire, in the room or space of its origin, at a time when the fire begins to threaten that room or space. After the ignition of a fire, it grows to a size with a flame body that can be as large as 0.6 to 0.8 m^3. If no person has dealt with the situation effectively up to this point, the sprinkler nearest the fire opens. The normal time delay between ignition and automatic attack of the fire is a valuable feature of the system.

An examplifying illustration of the effectiveness of an automatic sprinkler system as a measure for limiting the fire potential is given in Fig. 15 [41] . The figure demonstrates for four different types of fire loads in high-rise buildings the probability of success in control of a fire by a minimum type of sprinkler system

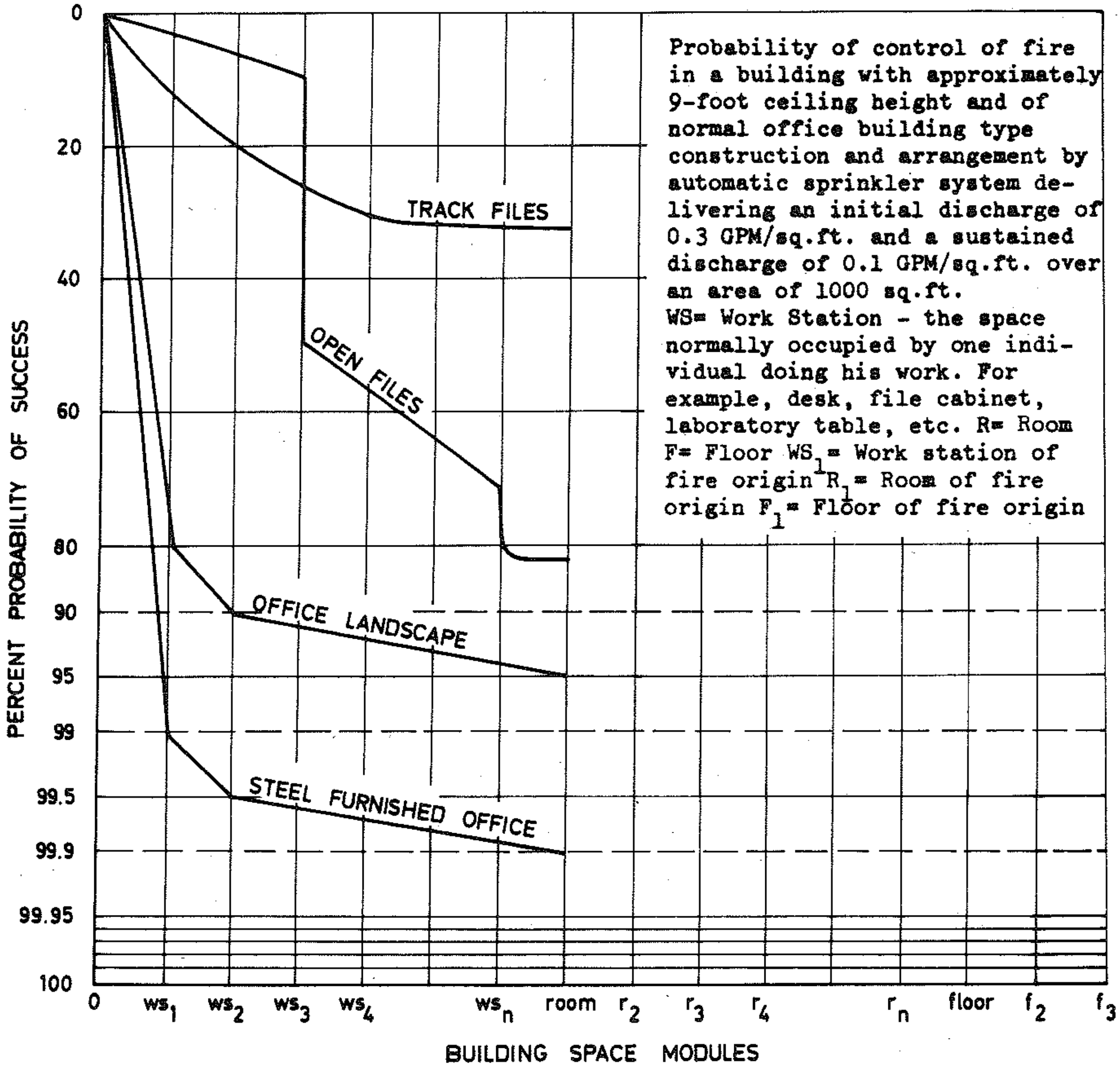


Figure 15. Percent probability of success for control of a fire at a specified automatic sprinkler system and at four different types of fire loading [41]

such as may be considered for office buildings. The curves are representative to building characteristics of approximately 2.7 m ceiling height and normal office building type construction and arrangements. The curves may be compared with the corresponding curves in Fig. 16 [41] , giving the probable limit of fire involvement for the same type of building if no sprinkler system has been installed. The probability determinations reffered in Fig. 15 as well as in Fig. 16 then are based on the presumption that all elements of structure and all elements of finish will be sufficiently noncombustible so that they will not contribute to fire growth.

The diagrams referred in Fig. 14 to 16 are examples of constituent elements of a goal oriented systems approach to building firesafety, introduced by the General

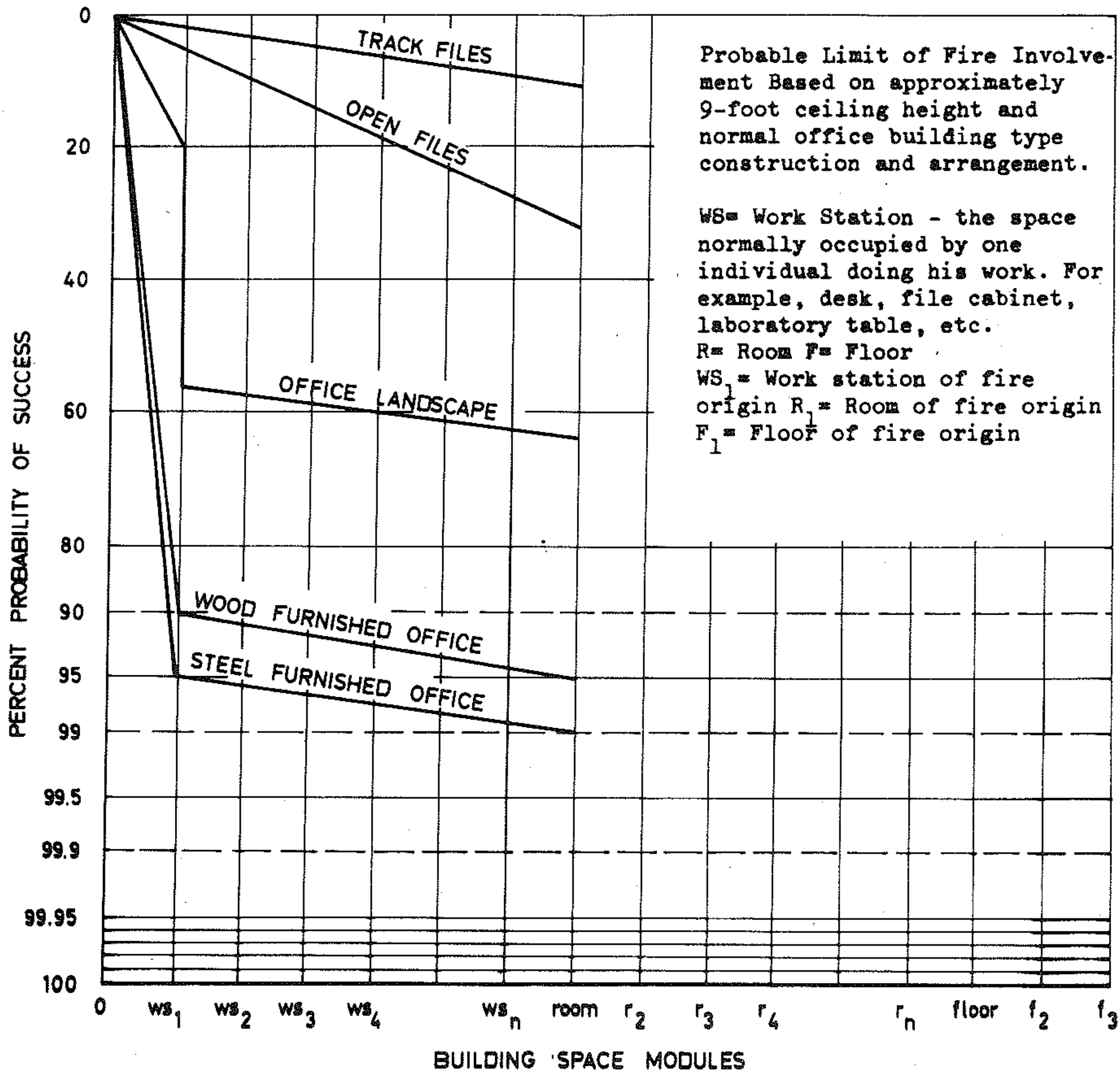


Figure 16. Percent probability of success for a limitation of fire involvement in a building without any sprinkler system at five different types of fire loading [41]

Services Administration, Public Buildings Service, USA to "be used in expressing and evaluating building firesafety for all new construction of all buildings over 100 000 square feet in gross floor area, all buildings having five or more stories above grade, and other buildings where directed" [41] . The diagrams are to be characterized as qualifiedly estimated on the basis of more or less extensive experience.

The firesafety system is structured as a decision tree network offering a number of interrelationships between relevant elements in a logic way. The system "points out which events must occur simultaneously or independently, it shows which events can contribute most effectively to reaching a goal, and it expresses the choices or tradeoffs available to insure a satisfactory goal or objective level" [41] . In the system, the levels of elements are connected by gates, either by an "and" gate or by an "or" gate. An "and" gate between two levels of elements then indicates, that all of the elements in the level immediately below the gate are necessary for the success probability of the element above the gate. An "or" gate between two levels of elements indicates an "and-or" relationship. That means, that a total inclusion of all of the elements below the gate is acceptable but not necessary for reaching the goal of the element above the gate. Exclusion of any element below an "or" gate, therefore, does not preclude the success probability of the element connected directly above that gate.

If the probability of success for a series of elements $\underline{B}_1$, $\underline{B}_2$ ... $\underline{B}_\nu$ ... $\underline{B}_n$ at a level $\underline{B}$ is denoted by p_{B_1}, p_{B_2} ... p_{B_ν} ... p_{B_n} respectively, then the probability of success p_A of achieving the goal-objective of an element $\underline{A}$ on a higher level is given by the formula

$$p_A = \prod_{\nu=1}^{n} p_{B_\nu} \tag{13}$$

when the $\underline{A}$-element and the $\underline{B}_\nu$-elements are connected by an "and" gate. For elements connected by an "or" gate, the corresponding formula is

$$p_A = 1 - \prod_{\nu=1}^{n} (1 - p_{B_\nu}) \tag{14}$$

Both formulas are valid under the assumption, that the events $\underline{B}_1$, $\underline{B}_2$ ... $\underline{B}_\nu$ ... $\underline{B}_n$ are independent.

For a chosen fire engineering design - given data of relevant elements - the probability of limiting the fire extent can be calculated as a function of the building space modules. The requirements with respect to the building firesafety are fulfilled, if the calculated probability of success is greater than the required one within the whole range of the building space modules. Requirements, reasonable for tall buildings, can be examplified by Fig. 17 [41] , showing mission-focused parameters for office type buildings according to GSA.

3.1 OCCUPANT PROTECTION

As has been concluded earlier, a tall building must be designed and maintained as a self-contained community from a fire engineering point of view. The building must be capable of maintaining its structural integrity during a fire over a period of time, determined by the actual fire conditions and the required safety level, meanwhile protecting its occupants and providing them with a safe means of refuge. Teams of occupants can be organized to attack the fire, particularly in the ignition, embryonic, and sub-room size stages. Outside support at the time of a fire by fire departments, police and other assistance will improve the capability of those in the building to defend themselves.

The fundamental concepts of occupant protection are [1]:

- limit the fire potential by fuel control, compartmentation, and automatic extinguishing,
- provide alternate protected ways out of the fire area to the safe areas of refuge,
- provide an emergency control centre - fully protected and equipped for dependable communication with all areas of the building and with outside sources of help,
- design and defend a "beachhead" on the critical ground-level floor, where stairs and elevators discharge, and
- establish an emergency leadership program for building occupants, including training.

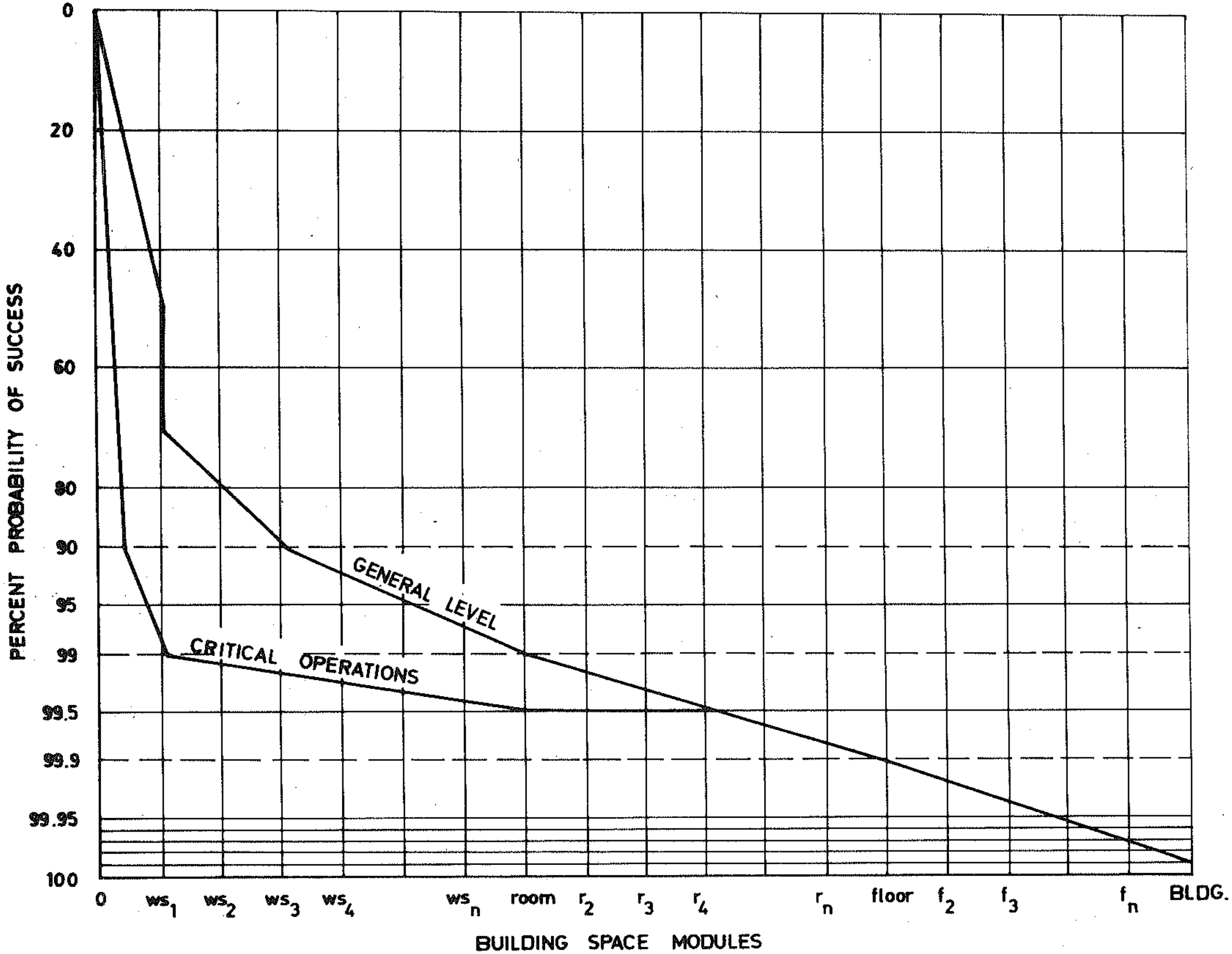


Figure 17. Mission-focused, parametric requirements for office type, tall buildings according to GSA, unless otherwise directed [41]

In a decision-tree approach, the occupant protection at a fire in a high-rise building can be summarized according to Fig. 18 [1], showing the overall occupant protection system divided into two main parts - the structural defense system and the public cofidence system - and subdivided into eight concepts in principal in agreement with the remarks above. Some of these concepts have already been discussed more in detail in the report, others will be treated summarily in the following chapters. In this chapter, the presentation only will be completed by quoting verbally from reference [1] the following procedures for the establishment of an effective high-rise training program, suggested to ascertain that all people that could be affected in the event of a fire emergency are well informed as to their duties and responsibilities.

Phase 1 - Building survey: A survey is made of the entire building. This familiarizes the Fire Prevention Team with the building in which they will be working. Any problems found are brought to the attention of the manager for correction.

Phase 2 - Fire brigade training: For the purpose of training maintenance personnel in the proper use of fire extinguishers, other first-aid fire fighting equipment, communication systems, and familiarization with their own facility.

Phase 3 - Tenant training: To establish an awareness of the need for a fire safety program, stimulate their interest and acquire their support. To familiarize them with the facilities available for their own safety. Floor Captains and Monitors are selected and trained. Floor plans for each floor indicating exits, first-aid equipment, etc. are reviewed. Methods and means of communication are discussed.

Phase 4 - Conducting actual drills: For the purpose of familiarizing the occupants with fire exits, towers and other means of escape. Actual fire drills are arranged and conducted in accordance with regulations promulgated by the Fire Department to insure the orderly evacuation of persons from the fire area. The drill includes the actual transmission of the fire alarm. The local fire companies assist in the drill by acting as drill observers. Upon completion of the drill, a critique is conducted to discuss problems and make necessary changes in procedures.

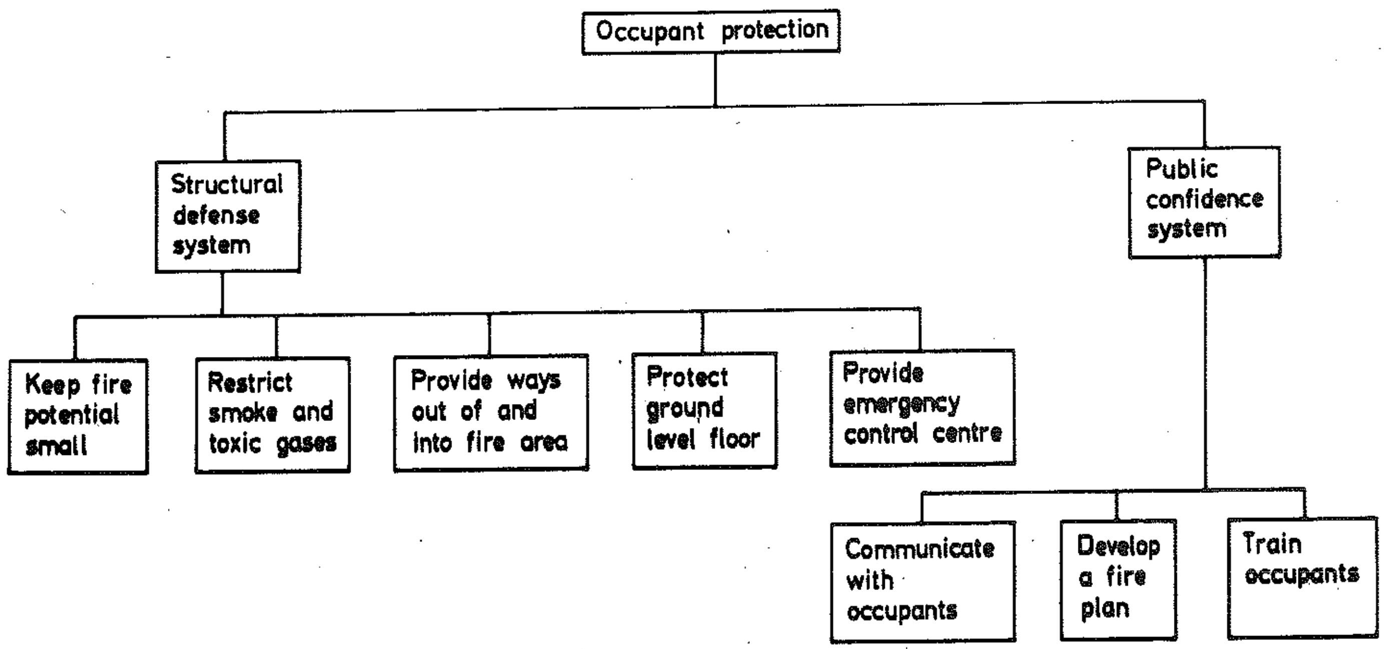


Figure 18. Overall occupant protection system for firesafety in tall buildings [1]

3.2 PERSONNEL MOVEMENT

The objective in protecting the occupants at a fire in a building is to avoid the imposition of intolerable conditions that will harm the occupants or psychologically intolerable conditions that will cause irrational behaviour [41] . In tall buildings, the basic methodology for attaining this is to provide a method and arrangement to move people from areas of danger to safe areas of refuge faster than either physiologically or psychologically intolerable conditions can develop in the areas of danger. The concept includes similar safeguards for the areas transversed and an ultimate area of safety that will not be affected by the fire conditions for the duration of fire exposure.

In [41] , these generally formulated requirements have been precised, as concerns the application to a fire engineering design of tall buildings with normal federal office type operations and with high hazard occupancies, respectively. The prescribed lifesafety parameters for occupants then are divided into three major segments of protection requirements: The immediate area of fire origin (normally floor), the emergency travel route from the immediate area, and the ultimate area of refuge.

For the segment immediate area of fire origin the following requirements are stipulated:

a. Normal Federal Office Type Operations

(1) All occupants exposed to the fire environment will be able to evacuate to a safe area within 90 seconds of alarm.

(2) A portion of this time, not to exceed approximately 15 seconds, can be involved in traveling in a direction which may be channelized towards the base of the fire.

b. High Hazard Occupancies

(1) All occupants exposed to the fire environment will be able to evacuate to an area safe from fire effects (including explosion effects, if such potential is involved) within 20 seconds of alarm.

(2) No portion of the travel route is to be arranged so evacuees must move in a direction that may be towards the base of the fire.

For the emergency travel routes, the same qualitative parameters are required for all occupancy classes. The total travel time to an area of refuge may exceed the limits given above. However,

(1) Upon leaving the immediate area of fire origin, when vertical movement is necessary, all occupants shall reach an ultimate area of refuge within five minutes of downward vertical movement or within one minute of upward vertical movement.

(2) Upon leaving the immediate area of fire origin, horizontal or vertical travel from or past the area of fire origin is to be within a safeguarded passage. The safeguarded passage will protect those within it from flame, high temperatures, intolerable thermal radiation, or atmospheres containing 3 % or greater contamination from the fire area.

For the ultimate area of refuge, finally, the requirements are given under the following form:

For all types of occupancies an area is considered safe for refuge from fire if it is free from flame intrusion, intolerable temperature, or painful thermal radiation; has sufficient oxygen for life support; and has an atmosphere environment the consituency of which contains 1 % or less contamination from the fire area.

For an emergency movement of occupants inside a building, three practical methods exist - stairways and elevators for vertical movement, and horizontal exits to fire safe areas. Of these methods only stairways and horizontal exits are currently recognized as emergency exits, while elevators generally are not fire safe. To provide for scheduled evacuation in a tall building, it is essential that the fire safety factors in the design of elevators be re-evaluated to assure that elevators will function as a safe means of transportation even under fire exposure conditions. As summarized in SOA Report No. 3, possible solutions are: installation of elevators within smoke free elevator towers; access to elevators through smoke protected vestibules or holding areas; use of non fire-sensitive controls or automatic over-rides to assure that elevators will bypass a fire floor; and reliable power supplies to guarantee continuity of operation at the time of a fire.

3.3 LIFE SUPPORT SYSTEMS

Life support systems concern the maintenance of a life tolerable condition in areas of refuge or egress travel. The same condition applies to access routes and staging areas used by fire departments or other emergency personnel. The level of life support capability or purity of the environment then is to be determined according to prescribed lifesafety parameters of the type quoted in chapter 3.2.

The following basic objectives provide the framework of the life support system problem [1]:

- a communication system that automatically will provide a warning to building occupants and direction as to their immediate action,
- provide zoned areas within the building such that movement of occupants a few floors above or below the fire zone will place them in a refuge area of relative safety,
- maintain the building areas outside of the fire zone at a pressure level higher than that in the fire zone,
- provide a positive means of removal of smoke from the fire zone and maximum protection against smoke infiltration in other areas,
- a fixed extinguishing system may be needed to limit the generation and spread of smoke and toxic gases.

The main problem in this connection, the control of the smoke movement, can be tackled over numerous control concepts with the general consensus of using pressure differentials, in combination with structural elements. The method and mode chosen in the individual case must relate closely to the procedures for movement of people and must be tailored to fit the basic overall system concept for the building.

Three examples of conceptive evaluations relating the control of smoke movement to occupant movement and travel system concepts are referred in Fig. 19 to 21 [1], [41]

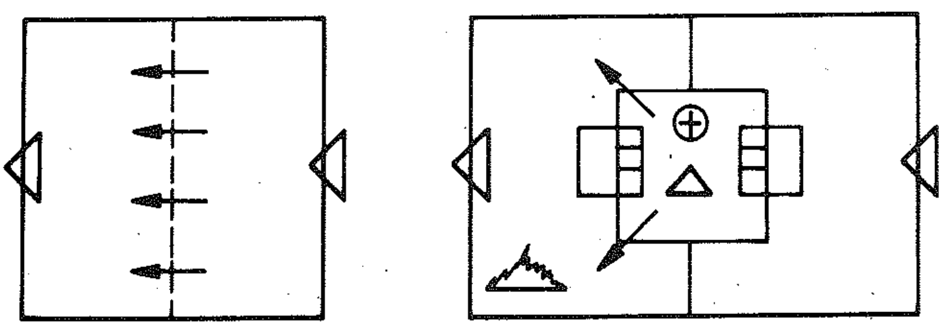


Figure 19. System for control of smoke movement - unbalanced in horizontal segments [1], [41]

Fig. 19 then shows the concept "Unbalanced in horizontal segments". By adjustment of fans, dampers, and/or vents, a pressure of air movement balance differential is established between side by side zones. Zones may consist of part of one floor, a vertical grouping of floor zones (parts of several consecutive floors), or an entire quadrant extending over the height of the structure. Upon detection of fire in a zone, the system converts so that the basic building balance is upset and the zone containing the fire is negative (vented) in relation to adjacent zone(s) (pressurized). The system is based on a continuous flow of air and a negative situation in the area involving the fire. The system may be used alone or in combination with systems balance in vertical segments and/or special shaft protection (stairs/elevators). Detection and initiation of the unbalanced situation can be by automatic detectors or by manual manipulation of the controls upon fire alarm or other instruction. Venting from the fire area may be through the return air system or by specially designed venting arrangement. Pressure would normally be provided by leaving supply air fans on in the areas not involved in the fire.

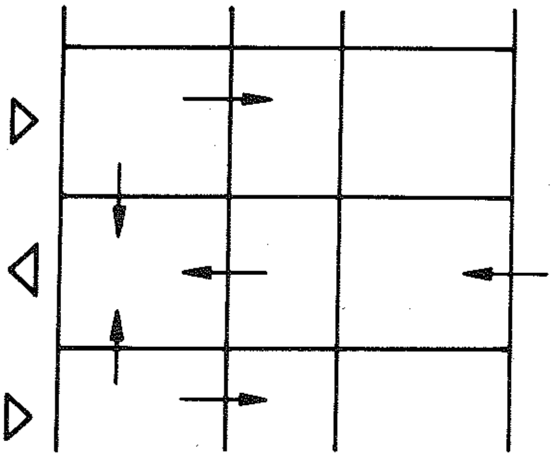


Figure 20. System for control of smoke movement - unbalanced in vertical segments [1], [41]

Fig. 20 explains the concept "Unbalanced in vertical segments". The building is divided into vertical smoke control segments consisting of one, or a group of adjacent floors, in each smoke zone. Adjustment of the fans, dampers, and/or vents develops a negative pressure situation in the zone containing the fire and positive pressure situations on adjacent zones. An air flow pattern is established to maintain a pressure gradient between the fire zone and adjacent zones and to maintain a flow of air from the adjacent zones to the fire zone. On detection of fire, the system is placed in operation by automatic or manual means. The system can work very effectively in any building having individual fans on each floor or where vertically stacked air zones exist. The system can readily be combined with the concepts of unbalanced in horizontal segments and/or special shaft protection (stairs/elevators).

Finally, Fig. 21 illustrates the concept "Special shaft protection (stairs/elevators)". A barrier is established to prevent the passage of smoke from a floor area into a stairwell or shaft by:
(a) pressurizing the shaft, or
(b) providing a negative vestibule between the building and the shaft.
Such a negative vestibule may be vented directly to the outside or maintained negative by other methodology. In some systems both concepts (a) and (b) are used in combination. The system can readily be used in combination with any other smoke control system.

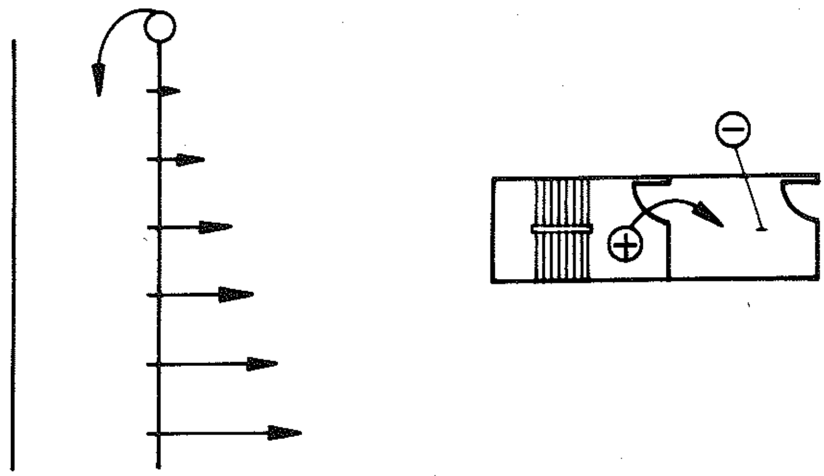


Figure 21. System for control of smoke movement - special shaft protection (stairs/ elevators) [1], [41]

3.4 EMERGENCY COMMUNICATIONS AND CONTROLS

The high degree of complexity of moving some occupants while desiring others to remain in place and of the possible need for even evacuating some occupants, necessitates zoned emergency communication systems and an emergency control centre in a readily accessible and strictly fire protected location, preferably on the ground level floor. Such an emergency control centre shall be capable of performing the following functions [1]:

- receive manual/automatic signal(s) from the fire area,
- dispatch signal(s) to fire department,
- communicate with occupants of fire area and in exits,
- initiate special elevator operations,
- initiate special mechanical system operations,
- communicate with occupants of nonfire area, and
- serve as fire department operations command centre.

The emergency control centre forms the focus for pre-ignition public relations, and post-ignition command. All communication cables from this centre should be electrically supervised and protected in an extra-secure manner from both fire and tampering.

The emergency control centre should be able to communicate with the occupants by both voice and visual devices (such as flashing signs, directional signals, television) to advise them of the emergency, and to issue warnings and directions, if necessary. The control centre must also be provided with signal systems, television monitors, or other means of quickly identifying the exact location of a fire and its extent, and of communicating with municipal fire fighting forces and other emergency aids. As mentioned earlier, the control centre also should be able to control certain of the buildings automatic equipment - most particularly operation of elevators, and air-conditioning systems which can be monitored against spread of smoke and fumes [1].

The detailed, complete system for building control in a high-rise building at fire is exemplified by Fig. 22 [1], showing the control system for the Seattle Federal Building, which is at present under construction with completion estimated for early 1974.

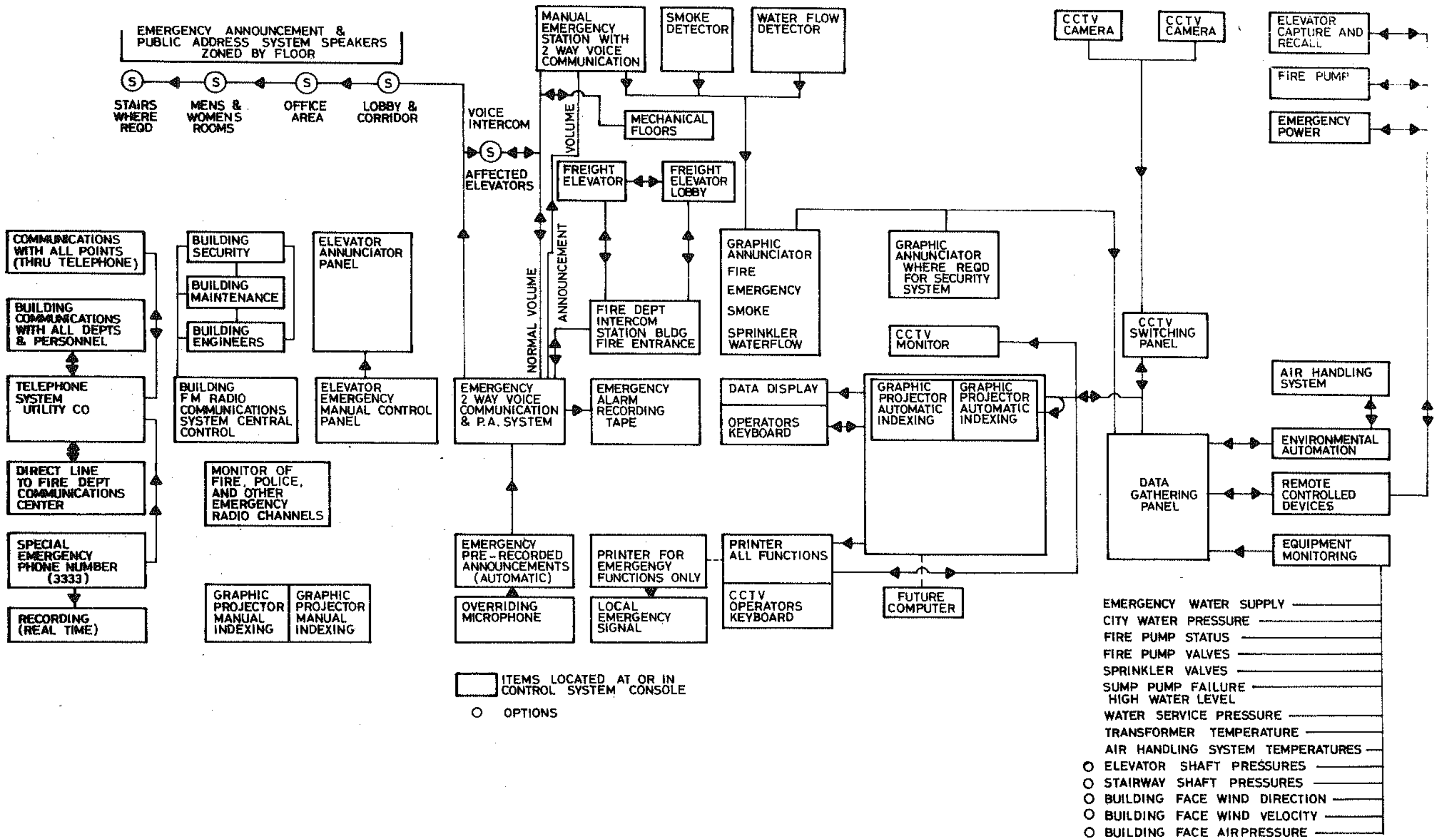


Figure 22. Complete system for building control at fire for the Seattle Federal Building [1]

3.5 STRUCTURAL INTEGRITY

Conventionally, the fire engineering design of a structure is based on a classification system, connected to a standard fire resistance test [43] to [45].

The scope of this test consists of a determination of the fire resistance of an element of building construction, defined as that period of time which extends from the beginning of a fixed heating process - the standard heating curve - to an instant when the element no longer complies with the functional requirements to be fulfilled. The function required then can be (a) a load-bearing function (e.g. a column or a beam), (b) a separating function (e.g. a partition or a non-load-bearing wall), and (c) a load-bearing and separating function (e.g. a load-bearing wall or a floor).

Fundamental for a fire resistance test is that the test results shall be reproducable. This necessitates very accurate detail specifications of the test conditions, as regards the preparation of the test specimens and the characteristics of heating, loading and restraint during the test.

Fundamental for a fire resistance test further is that the test results can be used in a structural fire engineering design as informations, representative for real conditions. This presupposes that the test characteristics and results have to be specified, measured and reported in such an extent and with such a degree of accuracy that the element of building construction, corresponding to the test specimen, can be analysed for a fire action with regard to its real functional behaviour in the complete structure. In detail accurately specified, measured and reported data for a fire resistance test also will facilitate a qualified classification and an international utilization of the test data in countries with different classification requirements.

In certain essential respects the present ISO Recommendation on fire resistance tests of elements of building construction has not been given such a form that the fundamental aims of the test can be guaranteed. Especially, this is the fact to the heating and restraint conditions, specified in the recommendation.

As concerns the heating conditions, the recommendation only specifies a time curve of the furnace temperature (the standard time-temperature curve), connected to additional directions for temperature tolerances and measurements. Such a specification is not sufficient as an external characteristic for a determination of the time-temperature fields in an element of building construction exposed to a fire. In addition, another decisive factor in this connection is the coefficient of heat transmission for the exterior surfaces of the fire exposed element, which coefficient primarily is influenced by the convection and radiation conditions. For a prescribed furnace time-temperature curve the convection and radiation characteristics can vary considerably from one furnace to another, depending on the detail design of the furnace and the type of fuel. Of that reason comparative estimations of test results, obtained in different fire engineering laboratories, can be very difficult - and sometimes impossible - to carry through. In order to facilitate such comparisons of test results, it is recommended in [44] that the thermal properties of the furnace shall be calibrated with reference to a well-defined standard test specimen and be described in terms of that variation in the coefficient of the average heat transmission with the time which is associated with the standard time-temperature curve. In [44] it is also recommended that such calibration curves of the furnaces shall be included in the test reports. Research work concerning such a thermal calibration procedure is at present in progress within CIB W14; cf. also [46].

As concerns the restraint conditions of a test specimen, it is well-known that variations of restraint characteristics considerably can influence the structural behaviour and the time of fire resistance for an element of building construction; cf. in this respect, for instance SOA Report No. 2. Usually the effect of increased degree of restraint is beneficial for the fire resistance of a structural element but sometimes a detrimental effect can be introduced. For instance, a thrust restraint can accelerate an instability failure in fire. For a concrete structural element, a thrust restraint also can give rise to an increased risk of spalling. For a statically indeterminate slab of reinforced concrete under fire action on one side, a moment restraint can cause a serious crack formation in weakly reinforced regions and owing to that initiate a shear fracture of the structure.

From these facts it is obvious that results from fire resistance tests, carried out under undefined restraint conditions - which is not infrequent today - are very difficult to use in a differentiated structural fire engineering design as well as for a qualified classification. The commentaries, given in [44] to the ISO Recommendation R 834, are intended to serve as a summary guidance for planning, performance, and reporting of a fire resistance test in conformity with the fundamental aims of the test, taking into account also the influence of various restraint conditions.

With distant aim, it may also be essential, in this connection, to pay attention to the fact that the present standard fire resistance test procedure principally can be called in question from a functional point of view. For instance, a fundamental improvement of the existing fire test procedure would be to replace the stipulation concerning a fixed temperature-time curve by a requirement which specifies fixed realistic time curves representing the combustion energy supplied per unit time to the fire testing furnace [3], [21], [47].

The present development of the building codes and regulations in the direction towards functionally better founded requirements will successively increase the necessity of replacing in the future the normal design procedure over classification by methods for a differentiated structural fire engineering design. During the last years several such design methods have been presented in the literature. Mainly, these methods can be divided into two different groups with respect to the basic data of the process of fire development. The methods belonging to the first group, then are characterized by a design procedure, directly based on gastemperature-time curves of the complete process of fire development, specified in detail according to Fig. 11. Characteristic for the methods of the second group is a design procedure with the varying properties of the fire development taken into consideration over a fictitious time of fire duration, connected to the standard time-temperature curve. In all methods of the two groups, the effect of the complete process of fire development - heating phase as well as subsequent cooling phase - is considered.

A more detailed presentation and discussion of methods for a differentiated structural fire engineering design will be given in Chapter 4. In that connection also the principles of the fundamental problem on the structural firesafety will be summarily treated.

3.6 FIRE-FIGHTING APPLIANCES AND CONVENIENCES

As emphasized previously, from a fire engineering point of view a tall building must be designed and maintained as a self-contained community.

Although the fire department should not be depended on in the initial critical fire stages, provision should be made to maximize their capability when they arrive at a high-rise building got on fire. Every effort should be made to enable them to be summoned promptly, to provide them with instantaneous information as to the location and severity of the fire upon their arrival at the building, to give them fast and safe internal transportation to the actual fire area, and to provide the building features and equipment necessary to enable them quickly and safely to attack the fire.

Prior to occupancy of a high-rise building, a written report ought to be submitted to the local fire authority giving a description and schematic drawings of all features relating to firesafety within the building. The report should contain information on the purpose and operating features of all firesafety devices including [1]:

- sprinkler systems,
- fire alarms,
- smoke detection devices,
- venting features,
- fire pumps,
- standpipes,
- exits,
- emergency lighting features, and
- compartmentation.

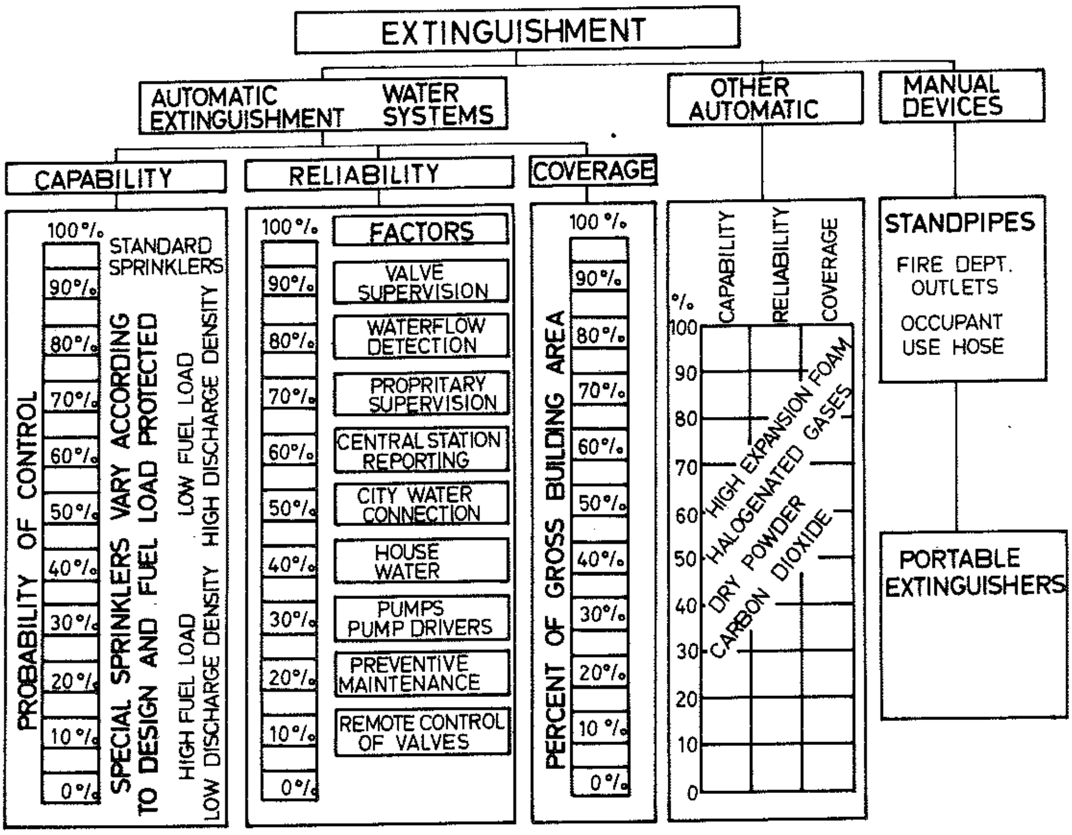


Figure 23. Graphic chart for a summary characterization of the extinguishing system in a tall building [1]

For a more detailed description and discussion of extinguishing systems and active fire fighting problems in tall buildings, reference is given to SOA Report No. 3, and partly also to SOA Report No. 4. In Fig. 23 [1], a graphic chart is presented which can serve as a basis for a summary characterization of the extinguishing system in a high-rise building. For the probability of control of a fire in a high-rise building by Fire Department attack, see [41] .

4. METHODS FOR A DIFFERENTIATED STRUCTURAL FIRE ENGINEERING DESIGN

As mentioned earlier in Chapter 3.5, several methods for a differentiated structural fire engineering design have been presented during the last years. Mainly, these methods can be referred to one of two different groups with respect to the basic data of the process of fire development. The methods of the first group are characterized by a design procedure, directly based on gastemperature-time curves of the complete process of fire development, specified in detail with regard to the influence of the fire load and the geometrical, thermal and ventilation properties of the fire compartment. Characteristic for the methods of the second group is a design procedure with the varying properties of the fire development taken into account over a fictitious time of fire duration, connected to the standard time-temperature curve. The methods of the two groups, which in their basic principles are equivalent and in their more specific details complete each other, generally are considering the complete process of real fire development - the heating period as well as the subsequent cooling down period - [3], [10], [45], and SOA Report No. 1.

4.1 STRUCTURAL FIRE ENGINEERING DESIGN, DIRECTLY BASED ON DIFFERENTIATED GASTEMPERATURE-TIME CURVES

Related to a load-bearing structure or structural element, a differentiated fire engineering design according to the methods of the first-mentioned group comprises the following main components [3], [7], [10], [48] to [50]:

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

(b) The determination for these combustion characteristics of the gastemperature-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 data on the strength and deformation properties of the structural material in temperature range, associated with fires - of the point of time for collapse at prescribed loading or, alternatively, of the minimum loadbearing capacity of the structure or the structural element for the process of fire development valid.

In a differentiated fire engineering design of a separating structure or structural element the design component (d), in most cases, is out of interest.

For making such a differentiated fire engineering design practically 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 behaviour and load-bearing capacity of the structure. Of particular interest in a structural fire engineering design of high-rise buildings then are computer programs enabling a thorough analysis of fire exposed multi-storey frames of high degree of statical indeterminancy: cf. for instance [51].

Examples of design diagram for facilitating a calculation of determining temperature and load-bearing capacity of fire exposed structures are given in Fig. 24 to 27.

In Fig. 24a-d [52] design curves are presented, directly giving the maximum steel temperature ϑ_{smax} for a non-insulated steel structure, exposed to fire on all surfaces, at varying opening factor $A\sqrt{h}/A_t$, fire load q, and quotient F_s/V_s. The resultant emissivity $\varepsilon_r = 0.7$. F_s is the fire exposed surface and V_s the volume of the steel structure per unit length. The diagrams are based on gastemperature-time curves of the fire compartment according to Fig. 11. For fire compartments with other thermal characteristics of the surrounding structures, the same design diagrams for ϑ_{smax} 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. 25a-d [52] show the maximum steel temperature ϑ_{smax} 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 material. The curves reproduced are related to an opening factor $A\sqrt{h}/A_t = 0.04$ m$^{1/2}$ and an emissivity $\varepsilon_r = 0.7$.

The problem of translating from a determining temperature to a load-bearing capacity of a fire exposed structure is examplified in Fig. 26a-d [50] , [53] . 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 exposed, axially compressed columns made of steel having a yield point stress at ordinary room temperature $\sigma_s = 2600$ 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 a column with imperfections 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. i = the radius of gyration and d = the distance from the gravity centre axis to the edge of the section of the column with maximum compressive stress.

As a final example of design diagrams, suitable for a differentiated structural fire engineering design procedure of the type summary described, Fig. 27 [54] gives the relationship between the allowed fire load q_{allow}, the width of the cross section b and the distance t from the layer of the reinforcement to the underneath side of a rectangular, reinforced concrete beam, exposed to a fire on three sides. The results refer to a critical temperature of the reinforcement $\vartheta_s = 510^oC$ and have been calculated on the basis of fire characteristics for a compartment with the opening factor $A\sqrt{h}/A_t = 0.04$ m$^{1/2}$ according to Fig. 11 with the influence of the cooling phase taken into account. The applicability of the results are marked in the diagram by horizontal arrows, connected to the ratio ν between the width b and the height h of the cross section.

Summarized a structural fire engineering design, directly based on differentiated gastemperature-time curves, is characterized by mainly a theoretical design procedure. The applicability in practice of this procedure, essentially can be facilitated by design diagrams, calculated for different types of structures or structural elements by means of computers. The design procedure is not connected to any need of classification and gives a low priority to the standard fire resistance test of

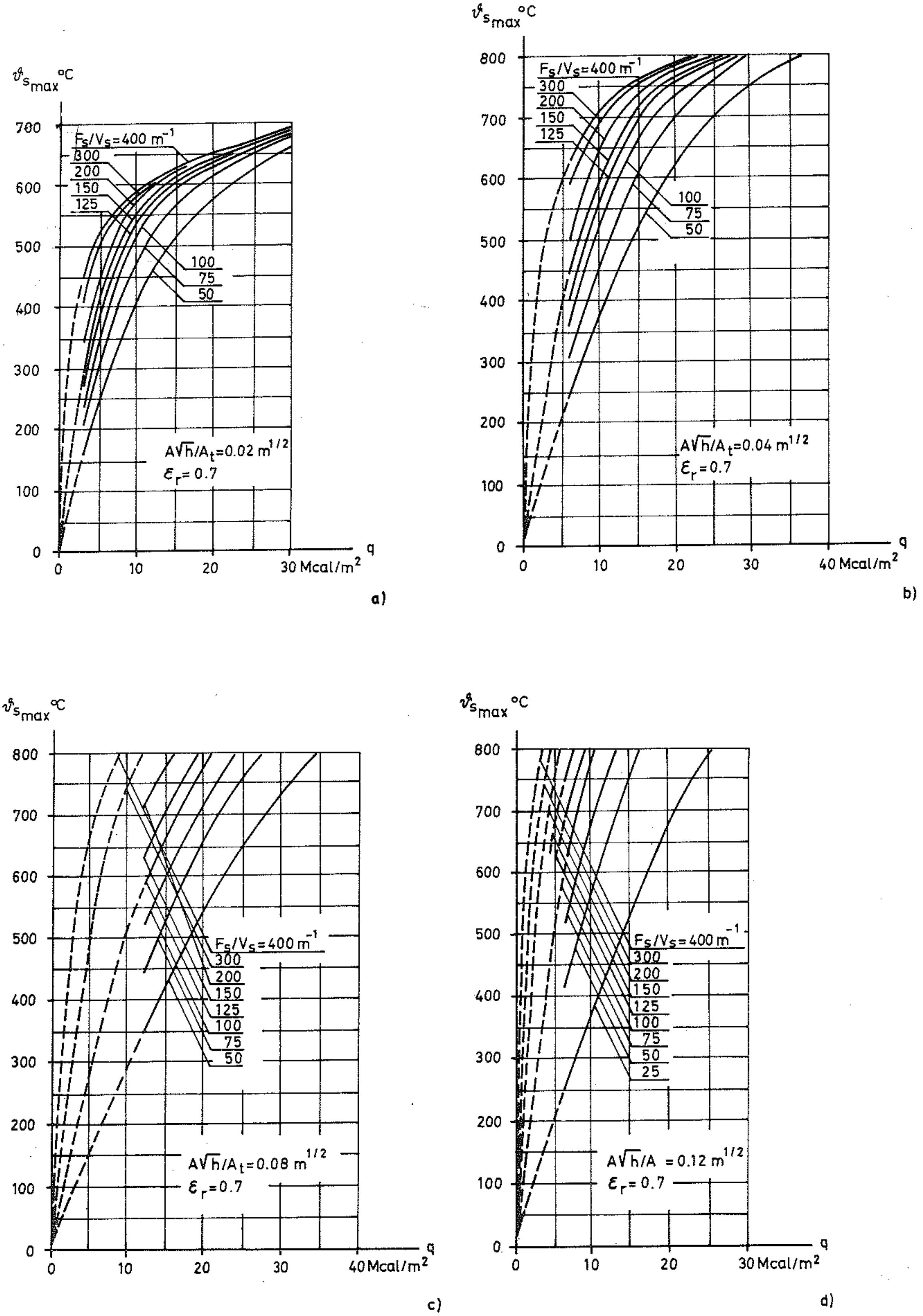


Figure 24. Maximum steel temperature $\vartheta_{s_{max}}$ for a fire exposed, non-insulated steel structure at varying opening factor $A\sqrt{h}/A_t$, fire load q, and quotient F_s/V_s. ε_r = 0.7. The curves are based on fire characteristics according to Fig. 11 with the influence of the cooling phase taken into account [52]

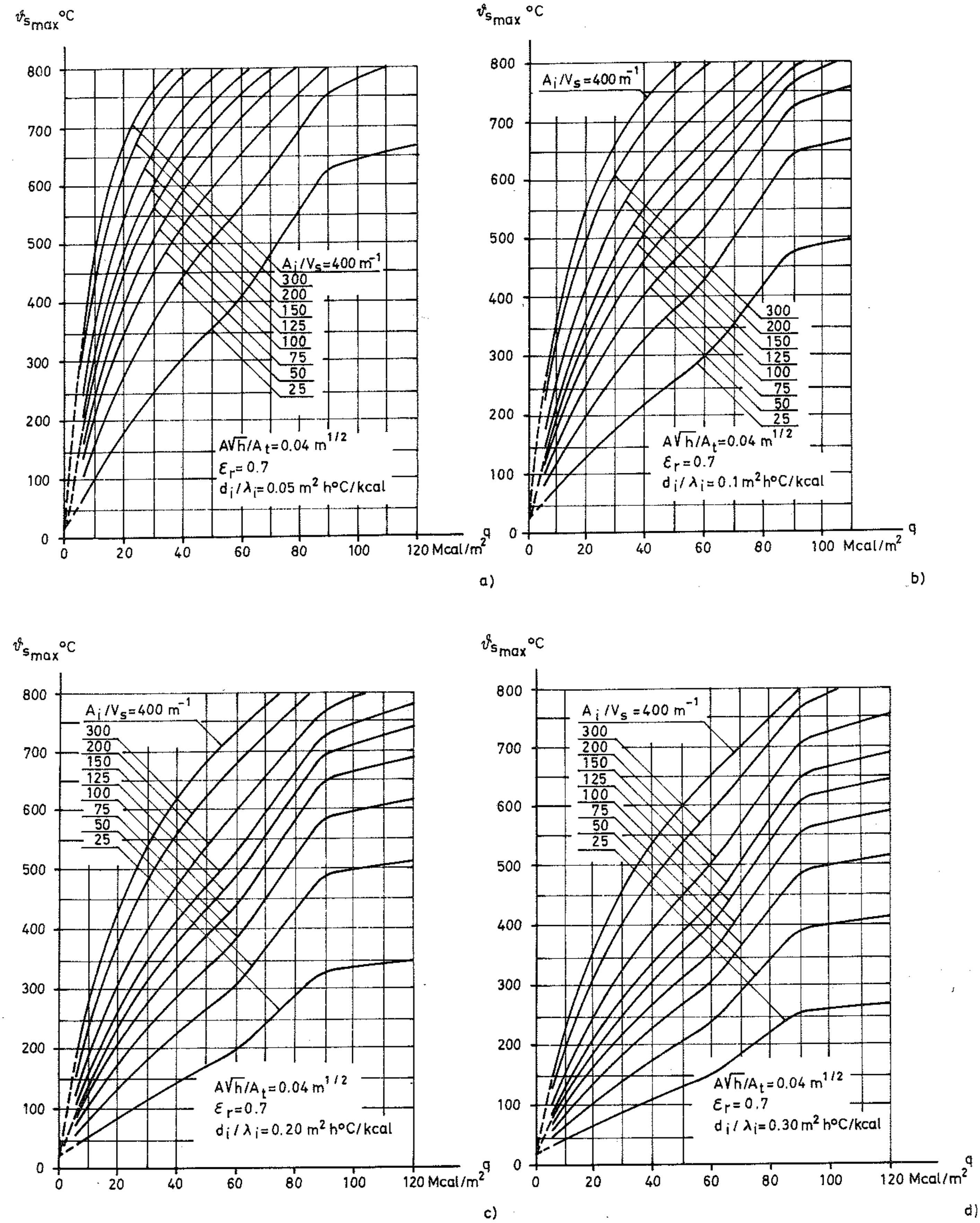


Figure 25. Maximum steel temperature $\vartheta_{s_{max}}$ for a fire exposed, insulated steel structure at varying fire load q, and structural characteristics. Opening factor $A\sqrt{h}/A_t = 0.04\ m^{1/2}$. $\varepsilon_r = 0.7$. The curves are based on fire characteristics according to Fig. 11 with the influence of the cooling phase taken into account [52]

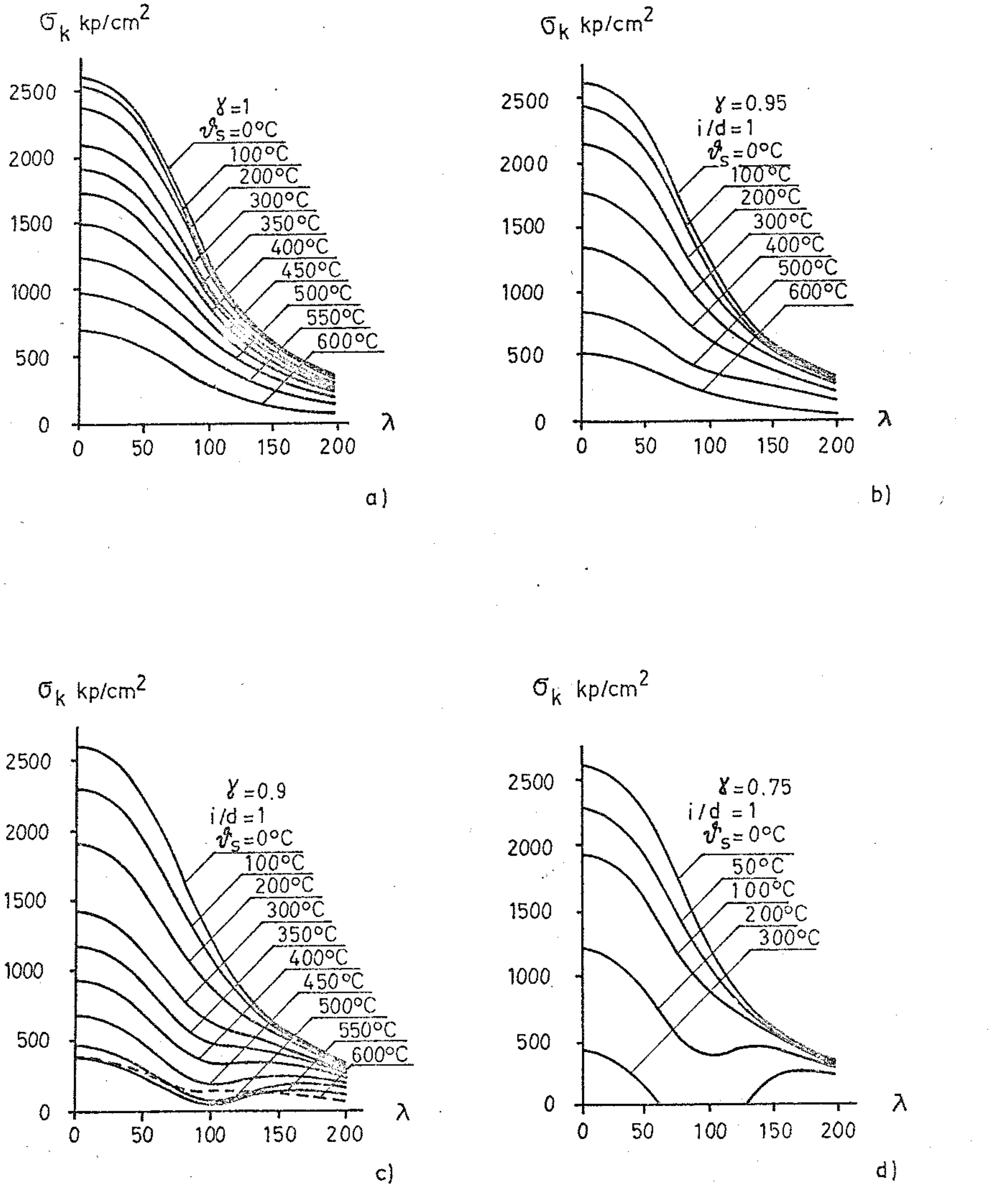


Figure 26. Variation with the steel temperature ϑ_s of the relationship between the buckling stress σ_k and the slenderness ratio λ for fire exposed, axially compressed columns, partially restrained to longitudinal expansion and made of steel having a yield point stress at ordinary room temperature σ_s = 2600 kp/cm^2 [50], [53]

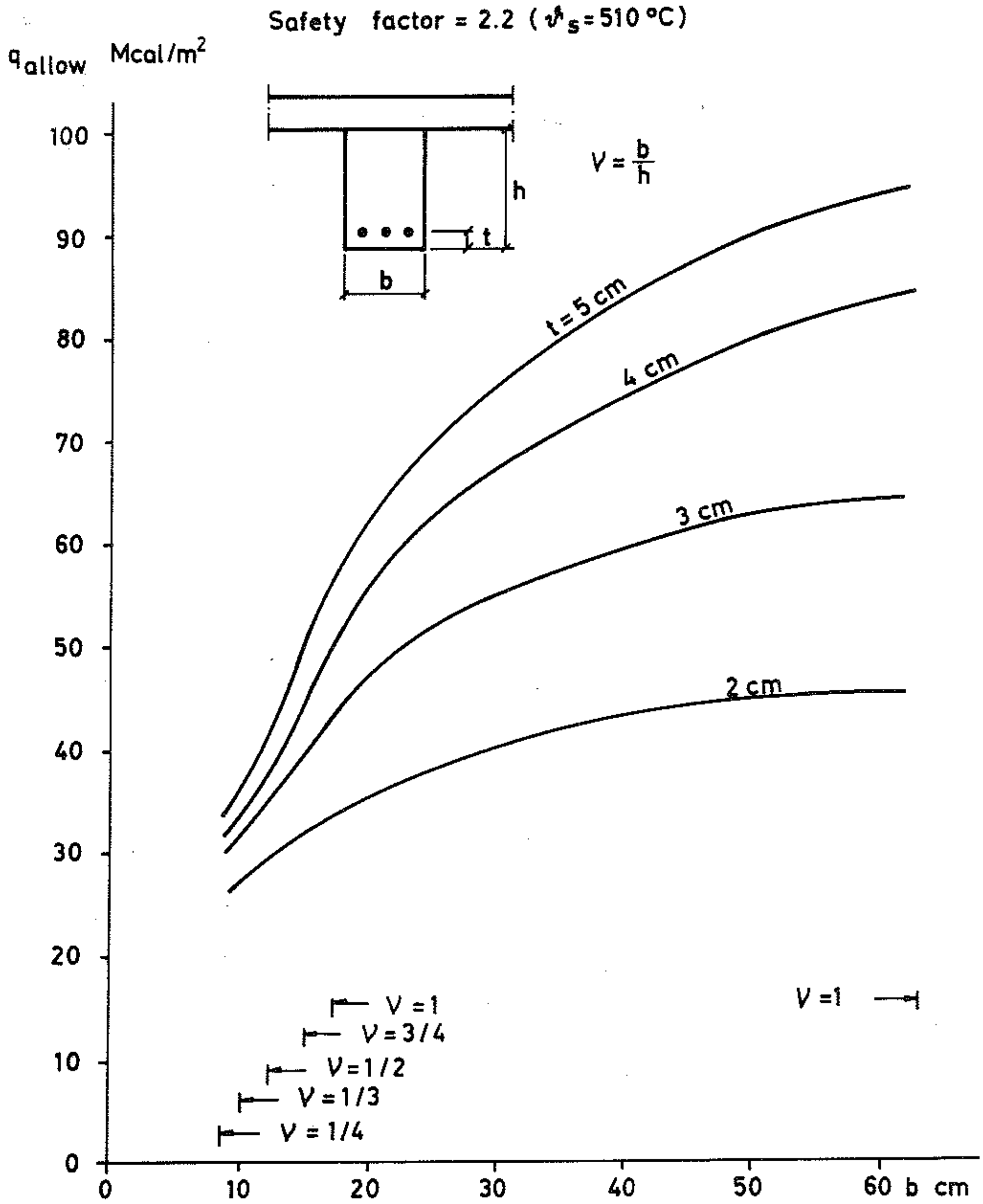


Figure 27. Rectangular reinforced concrete beam, exposed to a fire on three sides. Relationship between the allowed fire load q_{allow}, the width of the cross section b and the distance t from the layer of the reinforcement to the underneath side of the cross section. Critical temperature of the reinforcement ϑ_s = 510°C. The curves are based on fire characteristics according to Fig. 11 with the influence of the cooling phase taken into account [54]

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 for getting basic informations, necessary for the calculations. In those cases, when these basic informations depend on the detail 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, behaviour and strength of fastening devices for different types of insulation, rate of increase in the depth of the charred layer at timber structures – the design procedure can necessitate experimental investigations at gastemperature-time curves diverging from the standard time-temperature curve. In most cases, the data required then can be determined by essentially less extensive experiments than the standard fire resistance test.

4.2 DIFFERENTIATED STRUCTURAL FIRE ENGINEERING DESIGN, BASED ON A FICTITIOUS TIME OF FIRE DURATION

The concept fictitious or equivalent time of fire duration has been introduced to enable a direct translation from a real fire exposure to a corresponding heating according to the standard time-temperature curve. Depending on the level of accuracy intended, the character of the concept will vary. Up till now, three principally different definitions of the fictitious time of fire duration has been presented in the literature [10], [13], [20], [45], [55] to [57], and SOA Report No. 1.

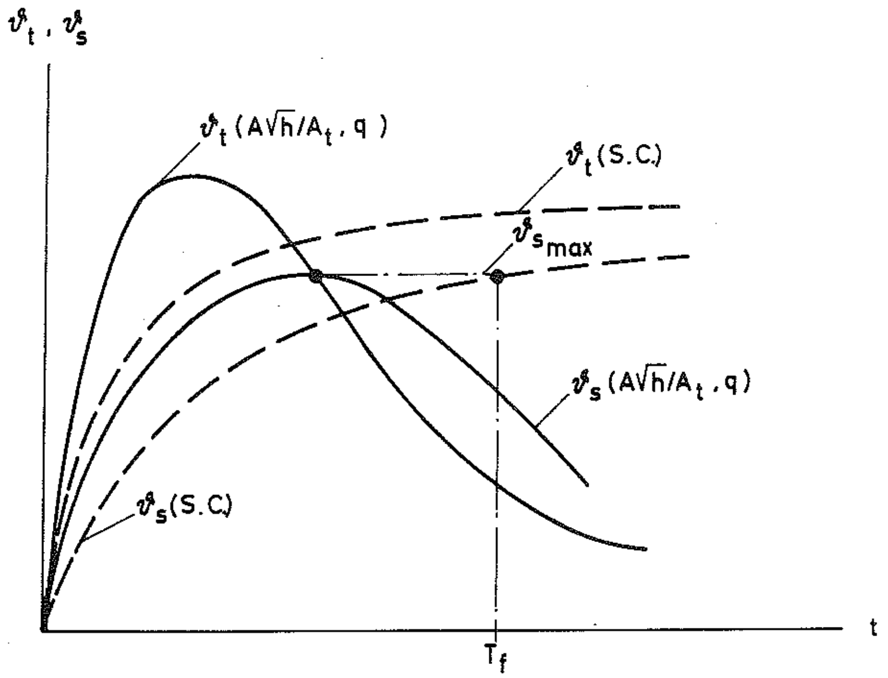


Figure 28. The principle of one method of evaluating the fictitious time of fire duration T_f, examplified for a fire exposed, non-insulated steel structure. The full-line curves refer the gastemperature ϑ_t and the steel temperature ϑ_s for a real fire action, characterized by the opening factor $A\sqrt{h}/A_t$ and the fire load q. The dash-line curves give the corresponding temperatures at a fire exposure according to the standard time-temperature curve (S.C.)

Examplified for a fire exposed non-insulated steel structure, one of the definitions given [10], [55], [56] can, in principle, be explained according to Fig. 28 which shows by the full-line curves the time-variation of the gastemperature ϑ_t and the steel temperature ϑ_s corresponding to a real fire action, determined by the fire load q, the opening factor $A\sqrt{h}/A_t$, and the thermal properties of the structures bounding the compartment. The dash-line curves give the standard time-temperature variation ϑ_t (S.C.) and the appurtenant time-curve of the temperature ϑ_s (S.C.) of the steel structure. A transfer of the maximum steel temperature $\vartheta_{s\max}$ for the real fire action to the curve ϑ_s (S.C.), belonging to the standard time-temperature curve, determines the fictitious time of fire duration T_f.

A modified way of defining the fictitious time of fire duration T_f has been presented in [13], [57] with special application to fire exposed insulated steel structures. Among elements of construction with varying thermal characteristics with respect to fire exposure that element is chosen, which for a given gastemperature-time curve of a real fire development gets a maximum steel temperature of a fixed value. T_f is then determined over the standard time-temperature curve for the same element and the same steel temperature. By repeating this procedure for different characteristics of real fires, a diagram can be constructed, applicable to a rough determination of fictitious time of fire duration T_f for an insulated steel structure, irrespective of the detail properties of the structure. An illustration of the method is given by Fig. 29 [13], based on results of a very comprehensive CIB model test investigation concerning the process of fire development and showing for insulated steel structures the fictitious time of fire duration T_f as a function of the parameter $L/\sqrt{AA_T}$. Then L is the total fire load of the compartment in kg, given as the equivalent quantity of wood, A the total area of the window and door openings in m^2, and A_T the area of the internal surfaces of the compartment in m^2 over which heat is lost. The figure gives a range of variation of T_f connected to varying porosity properties of the fire load, composed of cross piles of wood. Cf. also SOA Report No. 1.

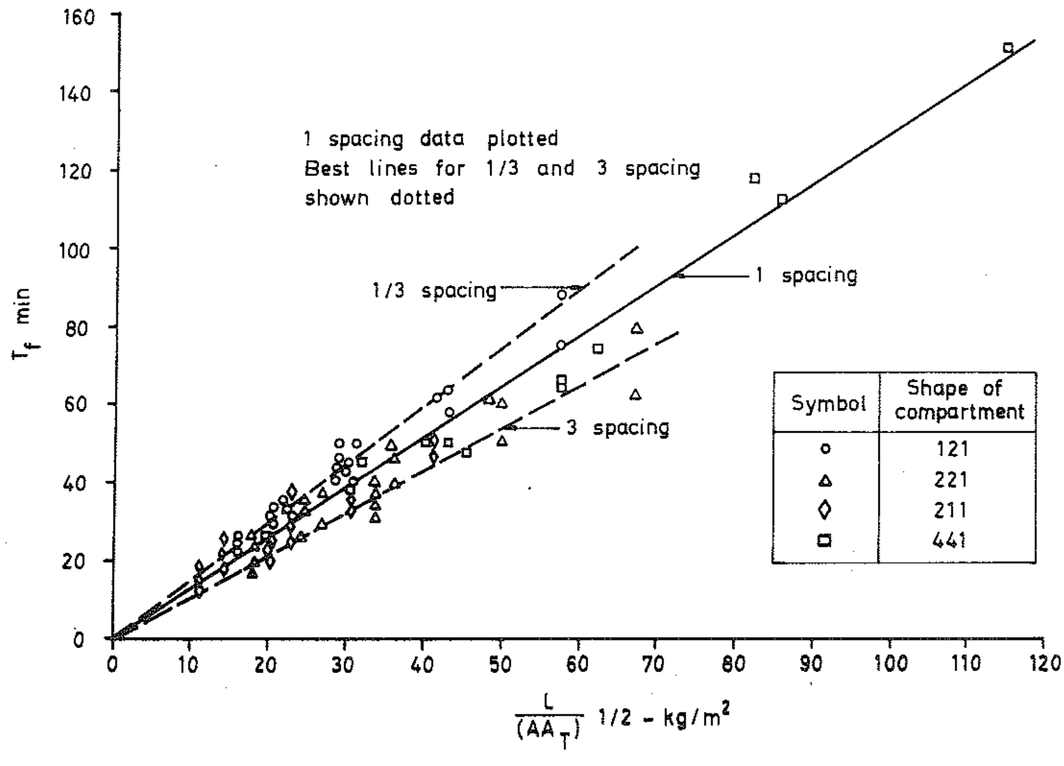


Figure 29. The fictitious time of fire duration for insulated steel structures T_f as a function of the parameter $L/\sqrt{AA_T}$ [13]

On the basis of the curves, presented in Fig. 11, a rough design diagram can be constructed, similar to the diagram according to Fig. 29. In studying the possibilities for doing so, it then has been found appropriate to use the parameter $M/\sqrt{AA_t\sqrt{h}}$ for a characterization of the compartment and fire load properties instead of the parameter $L/\sqrt{AA_T}$. This new parameter offers the advantage, that the influence of varying shape of the window openings can be taken into account which gives as a consequence a smaller scatter of the results. Fig. 30 shows such a relation between the equivalent time of fire duration T_f and the parameter $M/\sqrt{AA_t\sqrt{h}}$. Approximately, the point values can be summarized by the formula

$$T_f = 0.28 \frac{M}{\sqrt{AA_t\sqrt{h}}} \qquad \text{(min)} \qquad (15)$$

The formula requires that the total fire load M is given in Mcal, the opening area A and the total area, surrounding the compartment, A_t in m^2, and the opening height h in m.

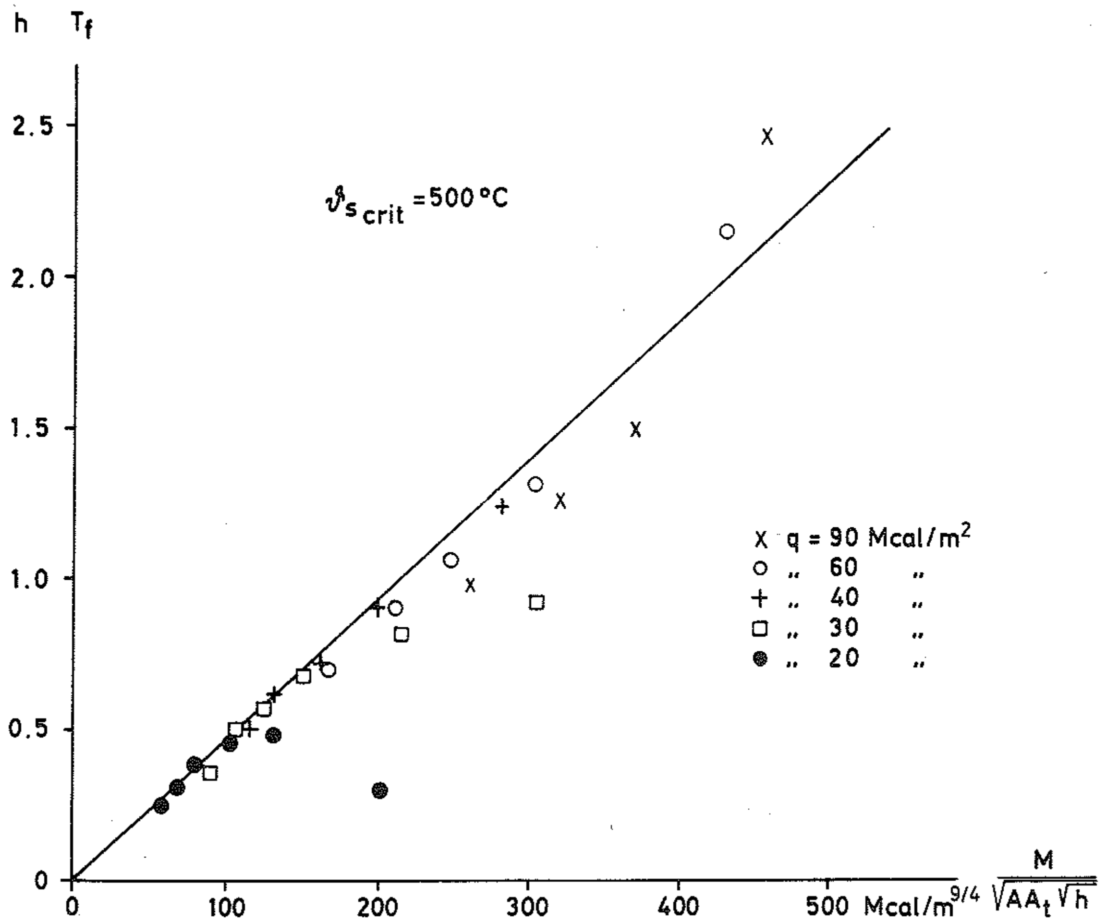


Figure 30. The fictitious time of fire duration for insulated steel structures T_f as a function of the parameter $M/\sqrt{AA_t\sqrt{h}}$

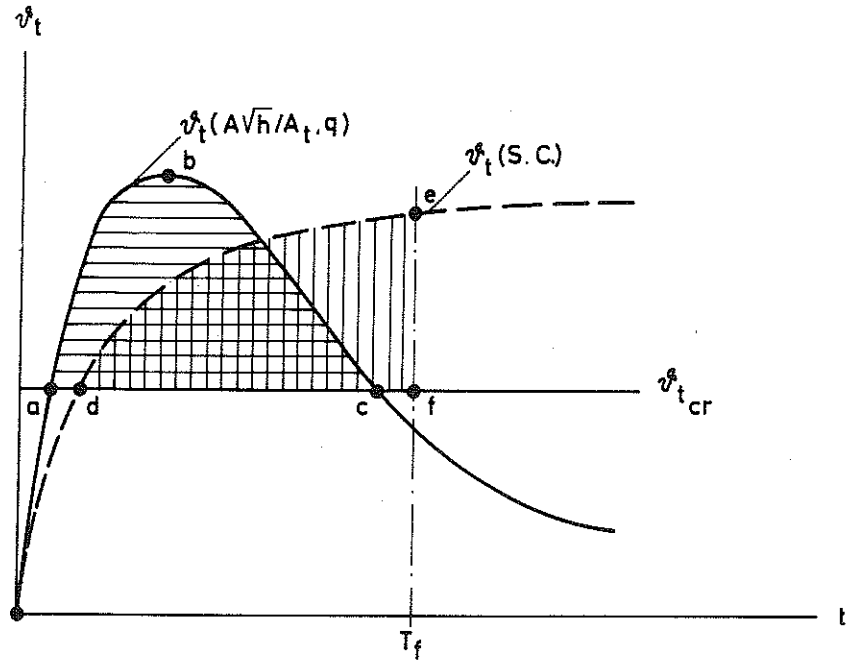


Figure 31. Fictitious time of fire duration T_f, defined according to [20] . The full-line curve refers the gastemperature ϑ_t for a real fire action and the dash-line curve the gastemperature according to the standard fire resistance test (S.C.). T_f is given by the condition that area (a-b-c) = = area (d-e-f) with $\vartheta_{t_{cr}}$ = a critical temperature with respect to the fire behaviour of the actual structure

A third alternative of introducing the conception fictitious time of fire duration T_f has been put forward in [20] . In principle, the alternative is illustrated by Fig. 31, which shows by the full-line curve the time-variation of the gastemperature ϑ_t corresponding to a real fire with a fire load q and an opening factor $A\sqrt{h}/A_t$ and by the dash-line curve the standard time-temperature variation ϑ_t (S.C.). For a given type of structure a temperature level $\vartheta_{t_{cr}}$ is chosen, which is characteristic with respect to the fire behaviour of the structure, and T_f is then defined by a condition, saying that the two areas between the respective gastemperature-time curves and the temperature level $\vartheta_{t_{cr}}$ are to be equal.

A determination of the fictitious time of fire duration T_f according to the second and third definitions leads to results, which are less accurate than a determination based on the fictitious time of fire duration according to the first definition.

Going back to this more accurate concept of fictitious time of fire duration T_f according to Fig. 28, it is evident from a functional point of view that T_f, given as determined by the fire load q and the opening factor $A\sqrt{h}/A_t$, commonly must depend on a great number of structural influences - for an insulated steel structure: the insulation material, the thickness of the insulation, the quotient A_i/V_s, and the resultant emissivity ε_r; for a reinforced concrete beam of rectangular cross section: the height h and the width b of the cross section, the distance t from the layer of reinforcement to a fire exposed surface, and the resultant emissivity ε_r.

Examplifying illustrations of the importance of such structural influences are given in [10] , based on the assumption that the real fire development is characterized by gastemperature-time curves according to Fig. 11. Some of these illustrations are referred in Fig. 32 to 35.

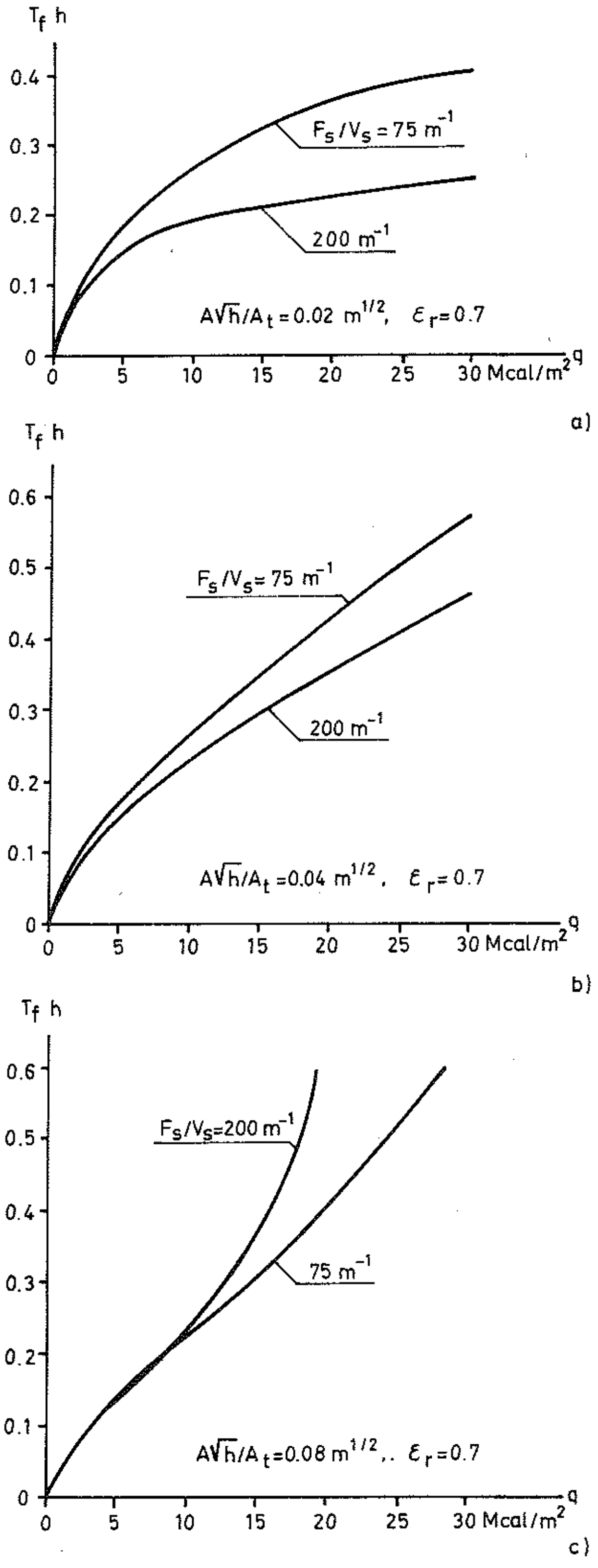


Figure 32. Fictitious time of fire duration T_f for a fire exposed, non-insulated steel structure at varying opening factor $A\sqrt{h}/A_t$, fire load q, and quotient F_s/V_s. Resultant emissivity ε_r = 0.7 [10]

By the curves in Fig. 32 then is shown the variation of the fictitious time of fire duration $\underline{T_f}$ with the quotient $\underline{F_s}/\underline{V_s}$ for a non-insulated steel structure. For the same type of structure with given characteristics, Fig. 33 complementary illustrates the influence on $\underline{T_f}$ of varying resultant emissivity $\underline{\varepsilon_r}$, as concerns the fire action according to the standard time-temperature curve. This problem is essential of the reason, mentioned above, that the radiation and convection characteristics in standard fire resistance tests can vary considerably from one furnace to another, depending on the detail design of the furnace and the type of fuel.

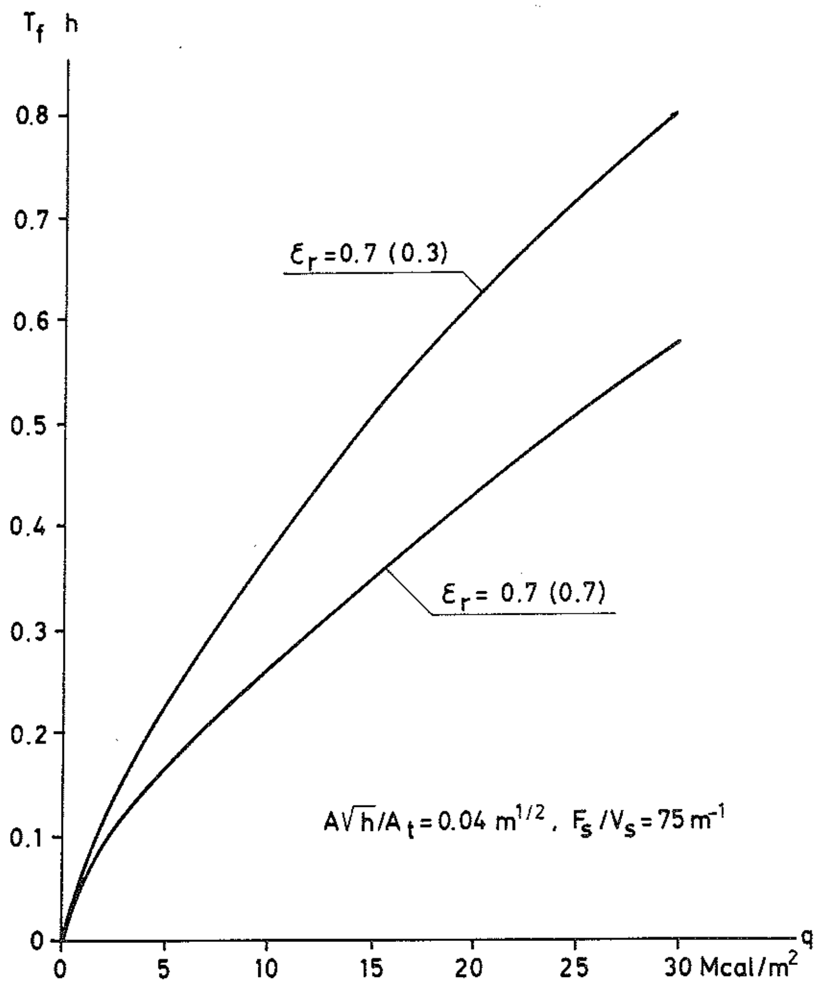


Figure 33. Fictitious time of fire duration T_f at varying fire load $\underline{q}$ for a fire exposed, non-insulated steel structure. $\underline{A\sqrt{h}}/\underline{A_t}$ = 0.04 $m^{1/2}$, $\underline{F_s}/\underline{V_s}$ = 75 m^{-1}. Both curves refer to a real fire exposure with a resultant emissivity $\underline{\varepsilon_r}$ = 0.7. As concerns the corresponding fire action according to the standard time-temperature curve, the upper curve presupposes a resultant emissivity $\underline{\varepsilon_r}$ = 0.3 and the lower curve a resultant emissivity $\underline{\varepsilon_r}$= 0.7 [10]

Fig. 34 examplifies the influence on $\underline{T_f}$ of variations in the opening factor $\underline{A\sqrt{h}}/\underline{A_t}$, the fire load $\underline{q}$, and the structural parameter $\underline{A_i}/\underline{V_s}$ for a fire exposed steel structure, insulated by a 13 mm thick gypsum plate, i.e. a product, which is disintegrated at a certain temperature condition.

Compared to each other, Fig. 32 to 34 for fire exposed steel structures illustrate the complex effect on $\underline{T_f}$ of variations in the structural design.

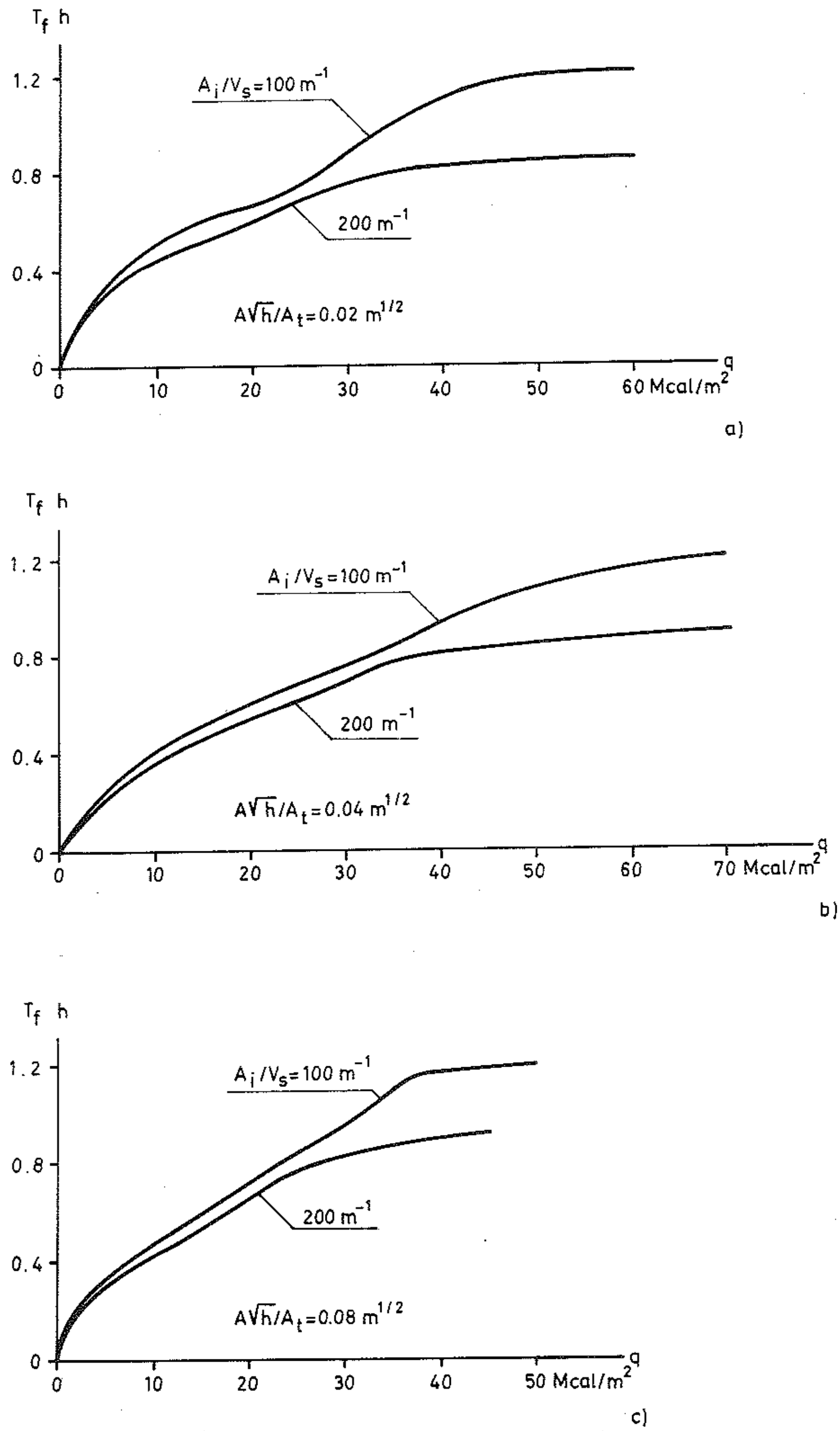


Figure 34. Fictitious time of fire duration $\underline{T_f}$ for a fire exposed steel structure, insulated by a 13 mm gypsum plate, at varying opening factor $\underline{A\sqrt{h}/A_t}$, fire load $\underline{q}$, and quotient $\underline{A_i}/\underline{V_s}$. Resultant emissivity $\underline{\varepsilon_r}$ = 0.7 [10]

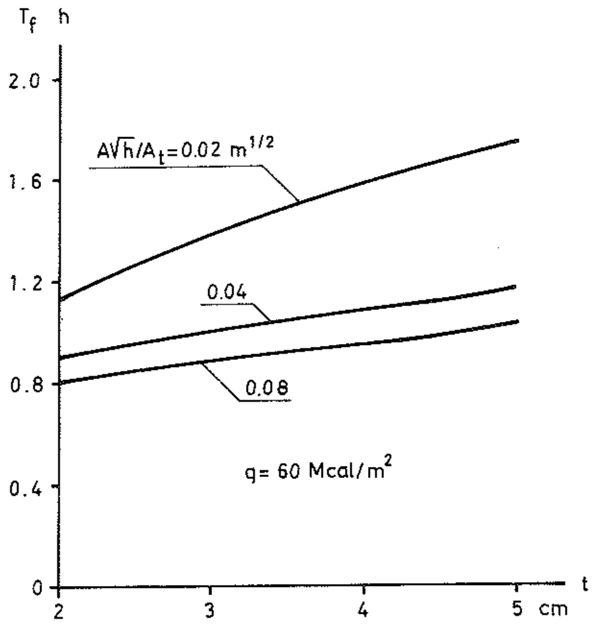


Figure 35. Reinforced concrete beam of rectangular cross section with height h = = 44.7 cm and width b = 22.4 cm, exposed to a fire on three sides. Fictitious time of fire duration T_f at varying opening factor $A\sqrt{h}/A_t$ and distance t from the layer of the reinforcement to the underneath side of the beam. Fire load q = 60 Mcal/m^2 [10]

Finally, Fig. 35 demonstrates the influence on T_f of varying distance t from the layer of the reinforcement to the underneath side of a rectangular, reinforced concrete beam, exposed to a fire on three sides.

From the results presented in Figs. 32 to 35 and in [10] the following conclusions can be drawn.

For a non-insulated steel structure the effect on the fictitious time of fire duration T_f of variations in the structural parameter F_s/V_s is considerable, especially for a fire development with a low value of the opening factor $A\sqrt{h}/A_t$. For an insulated steel structure, the corresponding effect - the influence of variations in the structural parameter A_i/V_s - is smaller. A change from a more resistant material of insulation to a material with disintegration properties then leads to an increased effect of variations in the parameter A_i/V_s within the temperature region above the first disintegration point of the insulation.

Differences in the radiation and convection characteristics of fire test furnaces can give rise to great variations in the fictitious time of fire duration T_f for non-insulated steel structures. For insulated steel structures the effect of such differences is less decisive.

From a summary comparison, based on the results presented above and in [10] concerning fire exposed steel structures, it is evident that variations in the structural design considerably can influence the fictitious time of fire duration T_f. The results reported for fire exposed reinforced concrete beams confirm this general statement by showing an obvious influence on T_f of variations in the distance t from the layer of reinforcement to the underneath side of the beam, especially at a fire development with a small value of the opening factor $A\sqrt{h}/A_t$ of the compartment.

From the discussion, it follows that a practical application of a differentiated structural fire engineering design, based on the accurate concept of a fictitious time of fire duration T_f according to Fig. 28, requires the use of design diagrams in about the same extent as a design procedure, directly based on differentiated gastemperature-time curves of the compartment. For both types of design methods such design diagrams have to be drawn up by a combined theoretical and experimental work with an extensiveness which is approximately equivalent for the two types. An advantage of the first-mentioned type of design methods is a better adaptation for a direct use of data from standard fire resistance tests. In favour of the last-mentioned type of design methods speaks a higher degree of suitability for taking into account such influences as varying thermal properties of the structures bounding the fire compartment, temperature-time dependent basic characteristics of the structural materials and of the details of the structure - for instance, effect of disintegration of the materials, enlarged short-time effect of creep and shrinkage, effect of crack formation and spalling, strength of fastening devices for different types of insulation, rate of increase in the depth of the charred layer at timber structures - and the detailed functional behaviour of the structure with regard to different types of fracture and varying load level and degree of restraint. The design methods, directly based on differentiated gastemperature-time curves of the compartment, also are better in agreement with the present development of the building codes and regulations in the direction towards more well-founded requirements.

4.3 PRINCIPLES OF THE STRUCTURAL FIRESAFETY PROBLEM

Generally, it is prescribed for a differentiated fire engineering design of load-bearing and separating structures that it is to be proved that the structures during the fire action are able to fulfil 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. Summarily, the corresponding problem of structural safety then can be principally described in the following way.

The load-bearing structure is acted upon by a loading which, for instance, can be a combination of the dead load and a live load. This loading then is characterized by a probabilistic variation which can be described by a frequency curve, comprising all those load levels L which will occur for the actual building or the actual structural element during its lifetime (Fig. 36). At ordinary room temperature, the load-bearing structure or structural element has a load-bearing capacity B with a probabilistic variation, determined by the distribution properties of the actual structural materials and the accuracy of the actual production and described by a frequency curve. A fire exposure will give rise to a decrease of the load-bearing capacity. At a given fire compartment - given characteristics of the geometrical, thermal, and ventilation properties of the compartment - this decrease depends on the fire load q, which for a given type of building or locality has a probabilistic variation with a corresponding frequency curve. Jointly, the frequency curves of the load-bearing capacity at ordinary room temperature and the fire load constitute the basis for a determination of the frequency curve of the least load-bearing capacity at a fire exposure B_f. In such a determination, then it must be included that change in the variation of relevant structural material properties which will be caused by the heating due to the fire exposure. Further, that uncertainty must be taken into account, which at a given practical application characterizes a theoretical determination of the process of fire development, and the connected temperature-time field and load-bearing capacity of the fire exposed structure or structural element.

If the frequency curve of the loading L and the frequency curve of the reduced load-bearing capacity of the fire exposed structure B_f are independent, the cor-

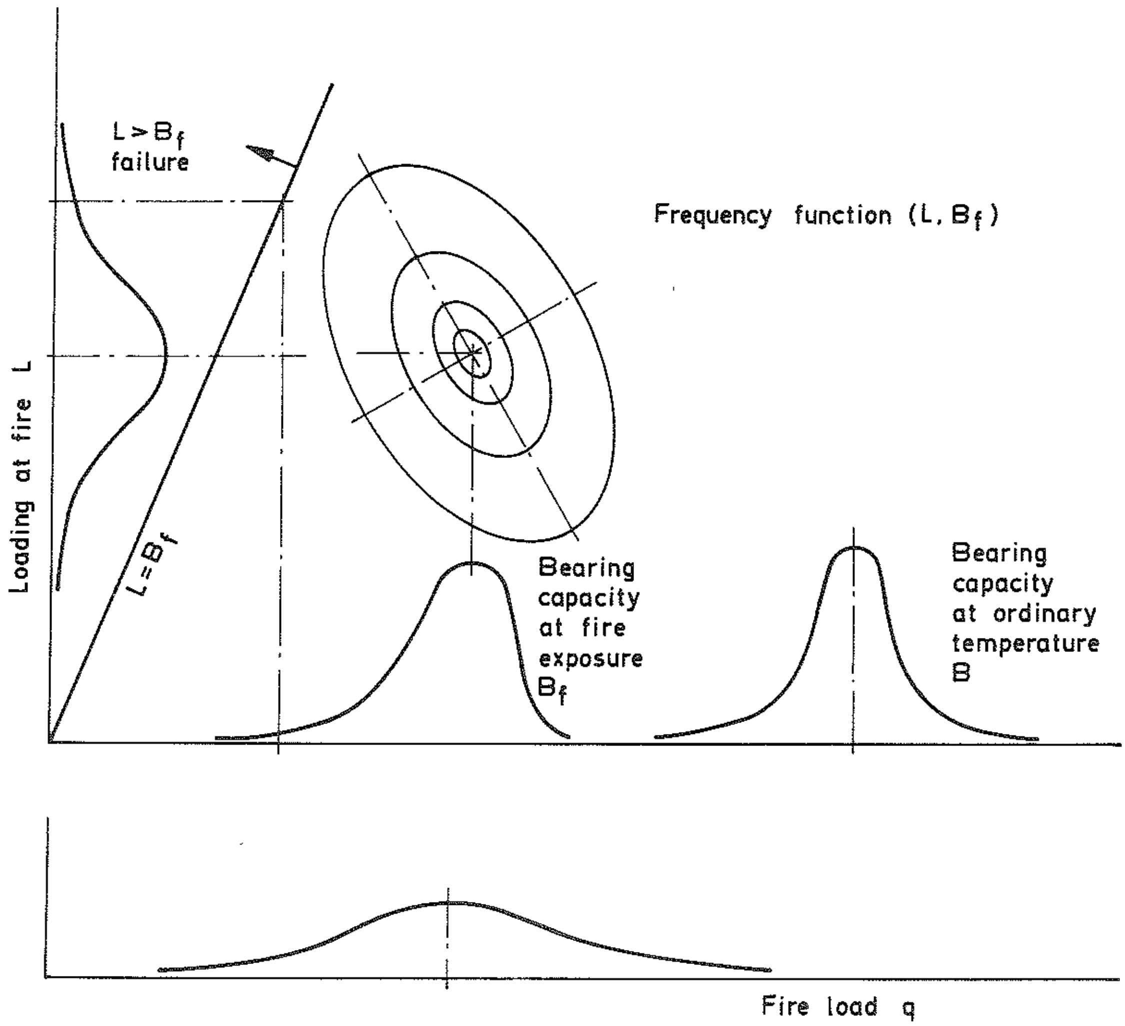


Figure 36. Summary survey of the structural safety problem at a fire engineering design of load-bearing structures

responding probability of failure at chosen levels of $\underline{L}$ and $\underline{B}_f$ can be calculated via a frequency function ($\underline{L}$,$\underline{B}_f$), given by a direct multiplication of the two frequency curves of $\underline{L}$ and $\underline{B}_f$. In a presentation according to Fig. 36, this frequency function ($\underline{L}$,$\underline{B}_f$) describes a surface above the horizontal $\underline{L}$-$\underline{B}_f$ base plane. If certain levels are chosen for the loading $\underline{L}$ and the load-bearing capacity at fire exposure $\underline{B}_f$, a vertical plane $\underline{L}$=$\underline{B}_f$ through origin is defined. That volume within the range $\underline{L}$>$\underline{B}_f$, which is cut off by this vertical plane between the frequency function surface ($\underline{L}$,$\underline{B}_f$) and the horizontal $\underline{L}$-$\underline{B}_f$ base plane, then gives the corresponding probability of failure, valid for a fire development not disturbed by any fire-fighting activities.

A probability of failure, calculated according to the described procedure, then is connected to a probability = 1 for a fire outbreak leading to flashover within the actual fire compartment. As a consequence, the calculated probability of failure must be corrected by a multiplication by the probability of a fire giving flashover in the compartment for the actual structure or structural element. For this latter probability, [58] gives the following representative values:

0.3 for industrial buildings,
0.04 for office buildings, and
0.02 for residential buildings

FIRE AND BLAST

KEY WORDS: emergency control, fire development, fire fighting, fire load, fire protection, fires, life support systems, occupant protection, personnel movement, safety, smoke, structural integrity, systems engineering, tall buildings.

The general concept of fire safety is analysed according to the principle of minimizing the sum of total investments and costs of fire damages. Points systems are touched upon and the principles of the structural fire safety problem are explained summarily. The fundamental characteristics of the fire load, fire growth, fully developed fires, smoke generation and smoke movement are presented and discussed. On the basis of this presentation, the principles are given of a differentiated structural fire engineering design which can be carried through either as directly based on real temperature-time curves of the fire compartment or via a fictitious time of fire duration, connecting real fire exposure characteristics with the heating conditions of the standard fire resistance test. A special chapter is devoted to some specific fire engineering design problems in high-rise buildings - such as occupant protection, personnel movement, life support systems, emergency controls, and fire fighting appliances - with a concentration on a systems approach.

at a lifetime of the buildings of 50 years. The referred values then are valid for a complete building and not for a single compartment of the building. Further essential reductions of the probability of failure in fire will be caused by, for instance, an installation of detection, alarm and automatic extinguishing systems with a probabilistic variation of operation security.

A computerized procedure for an analysis of the failure probability in fire of a load-bearing structure according to the principles described above, is presented in [59] . The procedure, which is based on the Monte-Carlo method, is connected to a differentiated structural fire engineering design according to Chapter 4.1. At present, the procedure can be applied in practice only in special cases. A more general application in a structural fire engineering design is for the time being rendered impossible as a consequence of insufficient knowledge concerning most of the variables entering into the procedure. In spite of these circumstances, the procedure ought to be successfully applied already, for instance, for a determination of such informations which can facilitate an elaboration of prescriptions in building codes and regulations concerning reasonable levels of loading and fire load for a structural fire engineering design of load-bearing structures or structural elements.

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