Trends in fire safety design of buildings

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1 Introduction

The last few decades have shown a rapid increase of the possibilities to understand and to influence physical and socio-economic processes, including building technology. This is due to the successful introduction of very powerful tools such as modern techniques based on computer applications and on the notion that the processes involved are essentially of a probabilistic nature. Also the fact that the possible means of information exchange have improved drastically has contributed to this development. In addition – at least in Western Europe – a political climate has emerged which is stimulating transnational cooperation and international orientation of research.
Within the field of building technology, fire safety design provides many excellent examples of the above-mentioned development. This paper will review some of these. Rather than dealing with technical or scientific details, a more general overview will be presented and an attempt made to outline some future developments.

2 The past

General review

From a long time past, fire has not only constituted a benefit to mankind, but also a serious threat. To control fire was a first step on the road to civilization. One of the aspects of this process was that people learned to protect themselves against unwanted fires. In more advanced communities, fire safety was not only seen as a responsibility of individuals, but increasingly also as a task of the community as a whole. This led to central planning of fire safety rules. Due to the restricted knowledge and technical possibilities, however, many fires have occurred which not only caused extreme losses but, in fact, threatened the survival of whole communities. History provides a number of illustrations of fires which resulted in almost total burn-out of whole cities. In The Netherlands such disasters occurred very frequently in the middle ages. The reason why especially in the middle ages these city fires occurred so often was the use of highly combustible materials such as timber and – especially – straw and thatch, in combination with extremely high building density. Such fires commonly gave rise to revision and reinforcement of the existing directives on fire safety. The earliest known fire regulations in The Netherlands are embodied in a city law of Ardenburg dating from 1232 [1] and requiring that thatch roofs be covered with incombustible materials such as clay or lead. Other rules specify the "fire protection" of facades and safe distances between buildings. Starting from the middle of the 15th century, building in timber was gradually superseded by building in stone-like materials, and the risk of fire consequently decreased. As far as the ability to extinguish fires is concerned, the introduction of the fire engine by Jan van der Heyden in the 17th century meant an important step forwards. At that time fire safety precautions and fire-fighting were still very pragmatic and based mainly on intuition and tradition. In fact, it was not until the beginning of the 20th century before a more rational approach became manifest. In this respect the systematic analysis of both the fire process itself and building's response to fire were important features.

Fire process

Although the fire process may be characterized in many ways - heat, smoke, toxicity - the early studies concentrate on the thermal effects.

In this respect it is important to distinguish between "fully developed" and "non-fully developed" fires. The term "fully developed" is introduced here to denote fire conditions under which all combustible materials in the compartment contribute to the fire. Gas temperatures of 800 °C or more must be expected. As a result, building components may be heated so severely that they loose their separating and/or load bearing function, so that the fire may spread to adjacent compartments. Also (major) collapse may occur. It will normally take some time for a fire to grow to the fully developed stage and often this will not happen at all. Under "non-fully developed" conditions the fire will only have a local effect and the average gas temperature will remain low. That is why - as a

Fig. 1. Fire in a 18th century city.

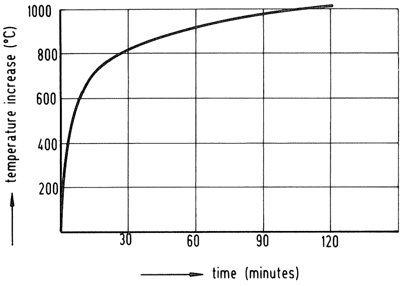


Fig. 2. The standard fire curve.

rule - the function of building elements at this stage of the fire is not endangered. Sometimes there is a fairly distinct transition point between "non-fully" and "fully" developed fire conditions. This is called flashover. Hence, the above conditions are also referred to as pre- and post-flashover conditions respectively.

The work on post-flashover fires by Ingberg in 1928 should be mentioned as one of the earliest examples of systematic investigations in the field [2]. The aim of the tests carried out by Ingberg - and by many others in subsequent years - was to analyse what factors govern the severity and the duration of fully developed compartment fires [3-6]. The main reason for starting such studies was the introduction of high-rise buildings in the United States and elsewhere, which called for more appropriate structural fire safety concepts. On the basis of these experimental studies, appropriate models were established in which the duration and the severity of compartment fires were related to the calorific value of the combustible materials only. The latter quantity was normally expressed in terms of kg wood equivalent per m^2 of floor area, the so called "fire load density". In an approximate way, fire duration appeared to be proportional to the fire load density. Although it was soon realized that other factors also played a part [7], it was assumed in the models that, apart from the fire duration, the temperature-time curve itself could be considered the same for all fires. These notions led to the concept of the "standard fire curve", giving the relationship between gas temperature and time during fully developed compartment fires, which is still the basis of traditional structural fire engineering design in many countries.

With the increasing variation in building design, better understanding of the fire process, as well as improvement of research facilities, the need was felt for a more differentiated approach. It was, however, not until the early sixties of this century that Kawagoe and Sekine in Japan [8] and Ödeen in Sweden [9], formulated the basis for more nuanced fire models, i.e. models in which the effect of the ventilation conditions could be accounted for. This was the start of a rapid development of more advanced fire models. As a result, a wide variety of computer models is now available, cf. for example [10-13], by means of which the gas temperature during fully developed compartment fires can be calculated as a function of time, taking into account factors such as:

- fire load density;

- ventilation conditions;
- thermal properties of the building components surrounding the fire compartment.

What all these models have in common is that the gas temperature is assumed to be uniformly distributed. Moreover, the rate of heat release is normally assumed to be controlled by the ventilation conditions only. Under these conditions, the heat and mass balance take a rather simple form and the gas temperature can be calculated as a function of time in a relatively easy way. The use of a high-speed computer is, however, indispensable. The above conditions may - in an approximate way - hold for post-flashover fires, they will certainly not be met when pre-flashover fire contitions apply. For pre-flashover fires a mathematical description of the heat and mass balance is, therefore, much more complicated. In fact, up to the present, no operational mathematical models are available in this field.

Apart from the thermal effects, smoke is an important feature of the fire process. In terms of life risk, smoke actually presents a more serious hazard than heat, while also the material damage due to smoke often is quite considerable. The amount of smoke generated during a fire depends not only on the materials exposed to fire, but also to a major extent on the exposure conditions. Already in the middle sixties Lie developed a small-scale experimental model on the basis of which a rough classification of building materials was possible in terms of optical density of the smoke produced [14]. In this model the exposure conditions were not varied, but a worst case situation was chosen. In the mean time more advanced experimental models have been established which allow a more differentiated determination of the smoke generation and - above all - a more realistic interpretation of the test results [15], [16]. At least as important as smoke generation is smoke propagation in buildings during fire. Developments in this field will be dealt with in the next paragraph.

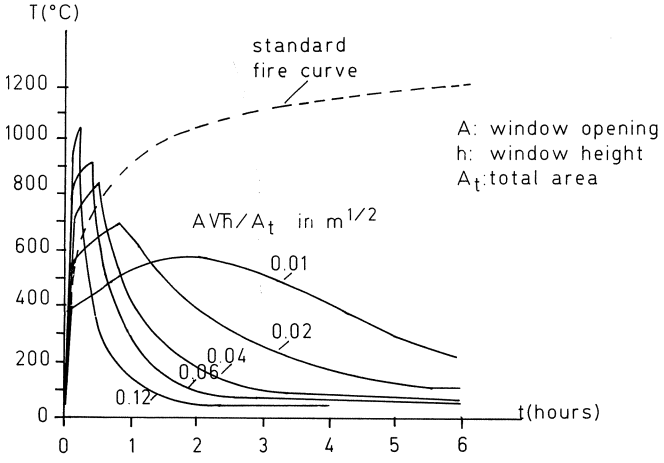
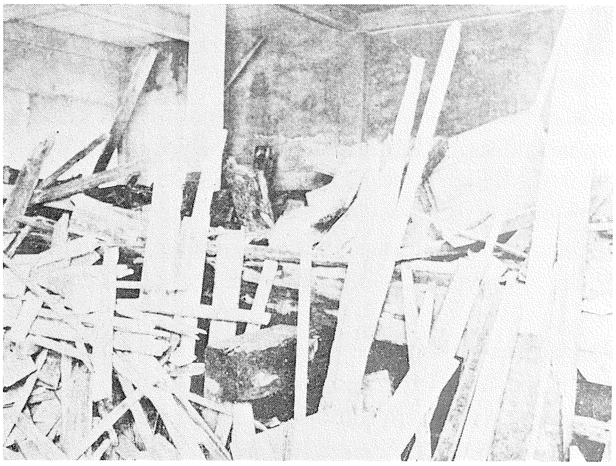
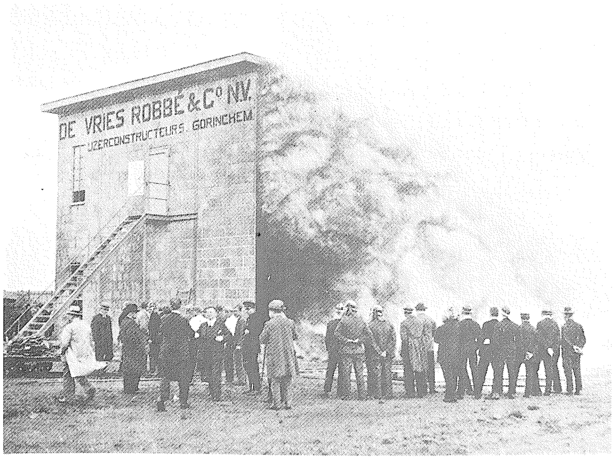


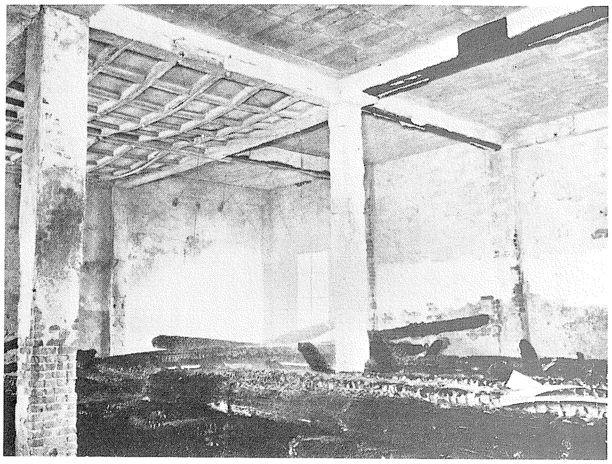
Fig. 3. Gas temperature as a function of time, calculated for various ventilation conditions [8].



a. the fire load



b. view of the fire test



c. fire compartment after the test

Fig. 4.
Full scale fire test carried out
in The Netherlands in 1930.

Building's response

The building's response to fire is highly dependent on the prevailing state of fire: either fully developed or not-fully developed.
The starting point for the assessment of the behaviour of building components exposed to fire was the fully developed compartment fire. Performance criteria were – and are – the ability of a building component to fulfil its separating and, possibly, its load bearing function during a period of time long enough to allow safe escape from the building and to prevent the fire from spreading to adjacent buildings. In the beginning, the analysis was based on ad-hoc testing. Figs. 4a, b, c give some idea of such a test, carried out in The Netherlands in 1930 [17].
Gradually a need was felt for standardizing the test procedure in order to improve repeatability and reproducibility. In the fifties this led to the introduction of the previously mentioned standardized relationship between gas temperature and time for fully developed compartment fires: the so-called "standard fire curve". Closely related to this curve is the concept of "fire resistance time", defined as the time a building element, when exposed to the standard fire and under conditions which are representative of normal practice, can fulfil its function. From that time on it became usual to carry out the tests in specially designed fire resistance furnaces. The first furnace of this kind came available in The Netherlands at TNO in 1952. Initially, each country developed its own version of the standard fire curve. It is a great merit of the Inter-

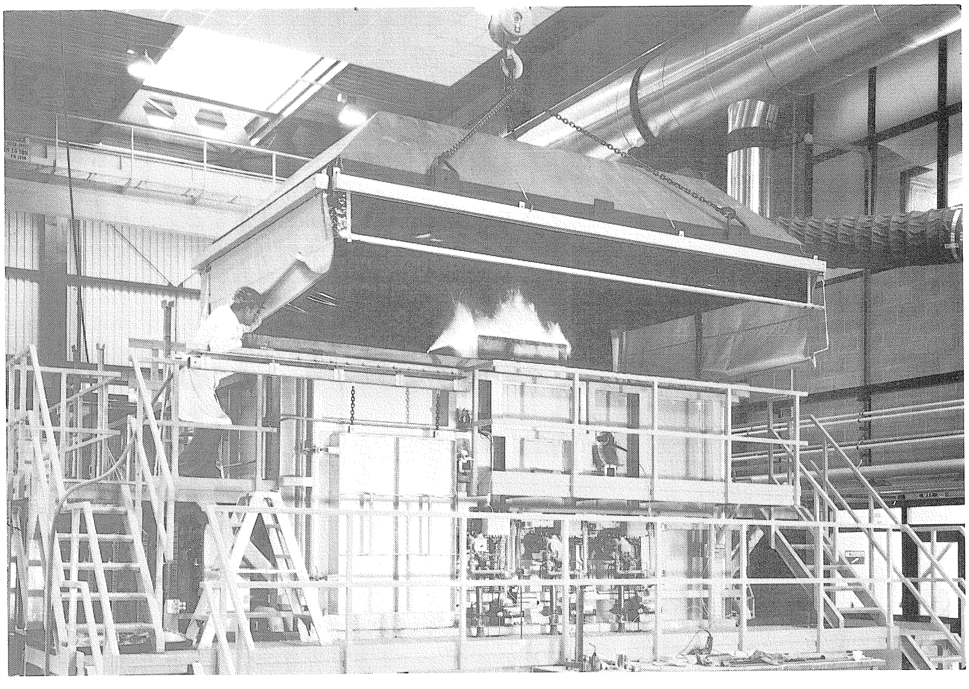


Fig. 5. Fire resistance furnace at TNO-IBBC for testing floors.

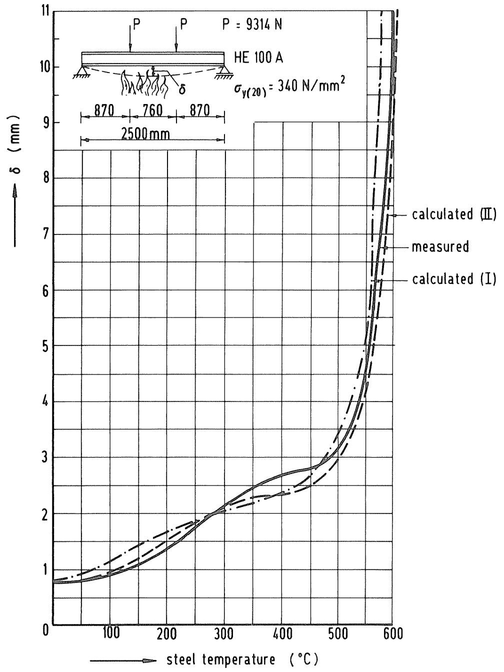


Fig. 6.
Calculated and measured mid-span deflection as a function of time of a steem beam exposed to natural fire conditions [27].

national Standardization Organization (ISO) that these different versions have been harmonized into one single curve which is now accepted practically world wide [18]. Although a very important step forward, standard fire resistance testing has also some major drawbacks, one of which is that it is difficult to extrapolate to other, non-investigated situations. Also the high costs and sometimes the long waiting times involved in testing are a disadvantage. Therefore, in the early sixties there emerged a trend to replace (standard) tests by calculations. One of the earliest examples is the calculation method for the fire resistance of structural steel, developed by Witteveen in 1963 [19]. This method was based on the application of simple plastic theory and allowed easy and rapid determination of the collapse conditions of loaded steel beams at elevated temperatures. In the following years the calculation methods were extended to load-bearing elements of other materials (concrete, timber) and were further refined [20–26]. Not only the calculation of the failure conditions, but an analytical description of the complete deformation behaviour of load bearing elements and structural systems under arbitrary fire conditions is feasible now.

Particularly in this field there was very intensive and fruitful international cooperation, and the stimulating role of international material organizations such as ECCS and CEB-FIP should be mentioned here [28–33]. The above mentioned development, however, is mainly confined to load-bearing building components. For non-load bearing elements, such as doors or light-weight partitions, no analytical models are available, and testing for fire resistance is still necessary.

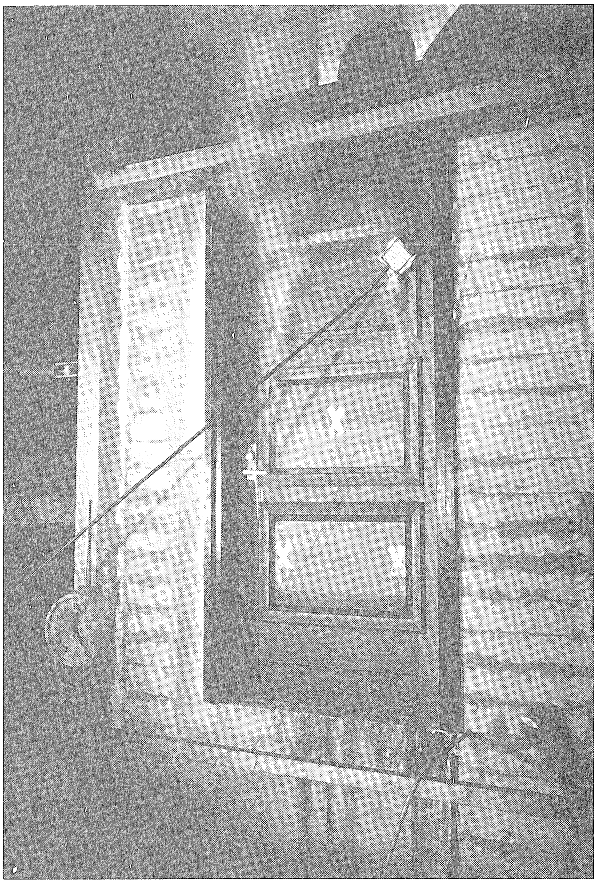


Fig. 7.
Testing of a fire door.

As mentioned before, the average gas temperature during the non-fully developed stage of a fire is – as a rule – not high enough to endanger structural components. Nevertheless this stage is of vital interest for the fire safety design of the building, inter alia, because its length determines to a major extent the possibilities for safe evacuation and early extinguishing. In the old days it was of course also realized that the ease of ignition and the contribution to fire growth was highly dependent on the materials applied. The best one could do at that time was to give a typological description of which products were allowed in certain situations, and which were not. The city law of Ardenburg of 1235, already mentioned, provides an early example of such an approach. Starting from the thirties of the present century, attempts have been made to arrive at a more functionally based classification system. A first step was to identify materials which under practical conditions do not contribute to fire growth. This led to the development of several test procedures [34], [35]. The most well known of these is the non-combustibility test. In this test the emphasis is on functional rather than on physical aspects. As a result, materials which are classified as non-combustible, may be combustible in a strictly physical sense. Combustible materials do contribute to fire growth; the extent of this contribution, however, may vary significantly for different materials. Therefore, in many countries classification procedures have been developed which allow further differentiation of combustible materials with regard to their reaction to fire. See for example: [36-39]. These are all experimental methods and - partly due to a lack of appropriate physical models for fire growth - they differ significantly from country to country.

To complete this section, some attention must be paid to the building's response towards smoke. As already mentioned, smoke constitutes a major hazard during building fires. Especially the speed and the extent of smoke propagation through a building, are of interest in this context. Models by which these phenomena can be described were, however, established only in the late seventies. The reason for this relatively late development is that experimental investigations on smoke propagation under fire con-

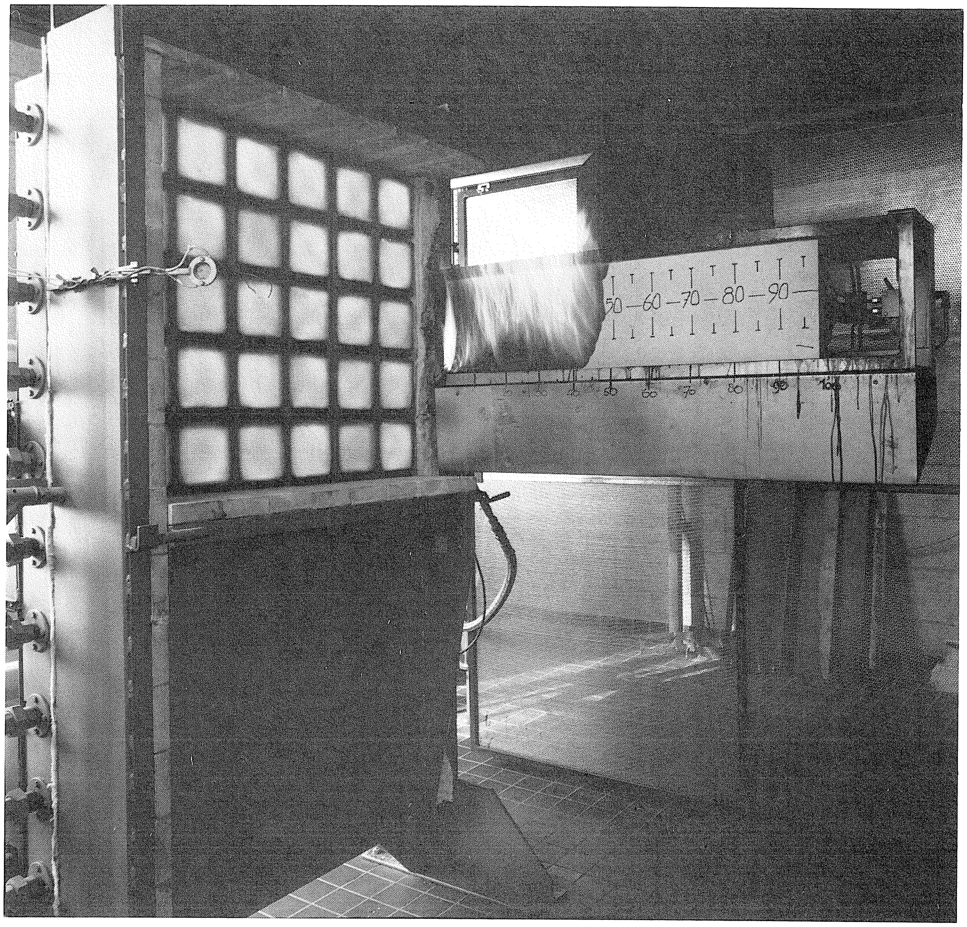


Fig. 8. The radiant panel, one of the experimental models by which the ease of ignition and contribution to fire growth is investigated in The Netherlands.

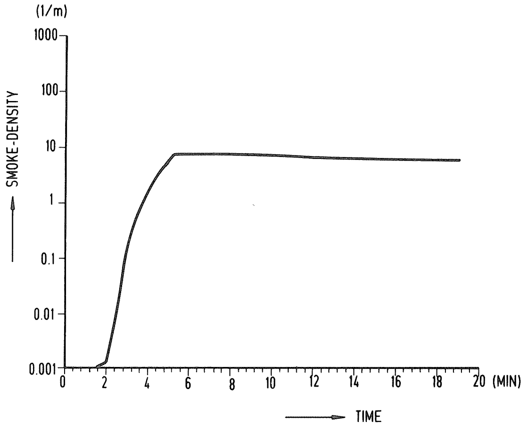


Fig. 9. The optical density as a function of time in the escape route of a high rise office building, calculated on the assumption of a fully developed fire in one of the offices [53].

ditions are problematical. Full-scale experiments are, for practical reasons, extremely cumbersome while the physical phenomena involved do not permit realistic experiments on a reduced scale. Analytical models call for powerful computers, which were not available until fairly recently. The introduction of such computers, however, opened the possibility of establishing computer models for smoke propagation, most of which are based on the assumption of uniform distribution of smoke in the various compartments of the building [40–44]. This implies that these models are only suitable for buildings with relatively small rooms, such as apartment buildings and traditional offices. Also, for this reason, stratification of smoke, which may be an interesting feature with respect to life safety in large rooms, is not taken into account. For some special applications - e.g. fires in traffic tunnels - TNO has therefore developed an approximate calculation method for analysing the conditions under which stratification may occur [45]. Other special applications in this field deal with the removal of smoke from the building by means of roof venting, see, for example: [46–49]. More sophisticated calculation models for smoke propagation under non-uniform conditions are in preparation at Delft University of Technology and elsewhere [50–52].

3 Present situation and future prospects

General review

Fire regulations play a dominant role in the present situation. In these regulations the requirements are specified which are to be met in various situations. As in most countries, in The Netherlands local government is responsible for public safety. Fire regulations are therefore issued on behalf of the local authorities and, in fact, are only valid within a certain municipality. In order to avoid too much local differences, a so-called "model building code" is established, in which also guidance is given on fire safety requirements [54]. This is intended as an aid for the local authorities in setting up their own regulations. Most of the municipalities have adopted the "model building code", sometimes with small modifications.

The Dutch fire regulations focus on so-called primary objectives, i.e. [55], [56]:

- safeguarding against loss of life and/or injury;
- preventing material damage to adjacent and surrounding buildings.

Prevention or reduction of material damage to the building on fire and its contents, commonly referred to as "secondary" objectives, are in principle outside the scope of the regulations. This is left to the owner and/or user of the building and to the insurance companies.

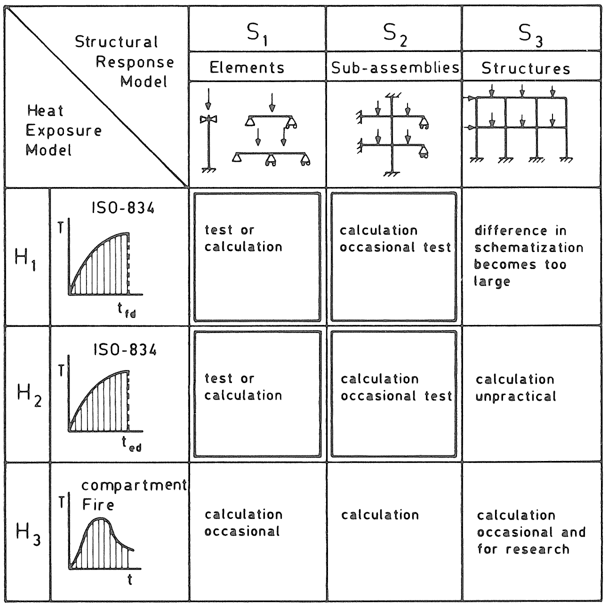
Special techniques and methods which are necessary to evaluate required levels of protection are specified in technical documents (standards) referred to in the regulations. The fire regulations and standards form a consistent system, based on the following principles:

- objectivity;
- consistency.

Objectivity implies a differentiated system which is based on a functional rather than on a typological description of products. In order to make the system suitable for practical use, the often very complex reality behind unwanted fires and their effects must be reduced to fairly simple models. Consistency refers to the necessary balance between the required levels of protection and measures necessary to meet these levels. This ensures a defined and uniform safety level.

The present situation as such can be characterized as rational and modern. However, in many respects it also has irrational features. The regulations, for example, focus on the thermal effects of fire, whereas smoke control is only marginally dealt with. The requirements related to the fire behaviour of building materials and building elements are fairly detailed. For the building contents - which may constitute a considerable fire risk - the requirements are only fragmentary, and for many applications proper models for evaluating the fire behaviour are not available. Only minor attention is paid in the regulations to the effect of active fire precautions such as automatic detection and extinguishing devices.

Such irrationalities are due to lack of knowledge, partly however also due to the traditional background of the present regulations and the inertia which is inherent in most legal systems. It is worth mentioning here that in The Netherlands the system of fire regulations is less rigid than in some other European countries, in a sense that alternative methods of assessment are accepted, provided they are based on proper evidence and/or sound engineering judgement. The way in which fire resistance of building components is determined affords an example of this approach. According to the standards, the only authorized way to do this is on basis of standard tests. However, starting in the sixties, calculation methods have been developed for the fire resistance, which offer significant advantages as compared with the traditional experimental methods. See also the discussion in the preceding chapter, under the heading "building's response". In an operational form such methods have been available for some years now, especially for steel and concrete. They are so widely used that standard fire testing on load bearing



Structural Response Model / Heat Exposure Model		S_1	S_2	S_3
		Elements	Sub-assemblies	Structures
H_1	ISO-834 T t_{fd}	test or calculation	calculation occasional test	difference in schematization becomes too large
H_2	ISO-834 T t_{ed}	test or calculation	calculation occasional test	calculation unpractical
H_3	compartment Fire T t	calculation occasional	calculation	calculation occasional and for research

t_{fd} = required time of fire duration
t_{ed} = equivalent time of fire exposure

Fig. 10. Matrix of heat exposure and structural models in sequence of improved schematization.

steel and concrete structures is very exceptional to-day. In general these methods are based on the traditional concept of fully developed compartment fires, i.e. on the standard fire curve. However, more differentiated approaches, e.g. the concept of the "effective fire duration" - a quanity which relates a non-standard or natural fire exposure to the standard fire - are also increasingly accepted. For a review of avialable methods, differentiated with respect to advised combinations of heat exposure and structural models, see Fig. 10 [57]. Of course, these methods have to be supplemented by the introduction of formalized rules which must be incorporated in the fire regulations and standards. In fact such a process is under way, and it will not be very long before the calculation methods for fire resistance will also be recognized officially [58].
A similar trend as described above, is developing in the field of smoke control methods [45], [49], [53], [59].
Apart from the developments discussed so far, there are some developments which are expected to have great impact on fire safety design in the longer term. These will briefly be reviewed below.

Advanced fire models

As mentioned earlier, the knowledge regarding the pre-flashover phase of a fire is still very incomplete, as opposed to the situation with respect to post-flashover fires. The reason is that a theoretical analysis was - until recently - virtually impossible because the physical processes involved are extremely complicated. Comprehensive experimental research was not feasible because of the excessive costs entailed by such research. Consequently, the present models for fire growth are based on concise experimental investigations, and their physical meaning is not very clear. These models, which play an important role in the classification of building materials with regard to their reaction to fire, therefore, have rather a conventional than a functional character. The consequences of this are as follows:

- differences between national classification procedures cannot be bridged;
- the effects of changes in building design on fire growth - especially with respect to window area, compartment size and thermal insulation - are difficult to estimate.

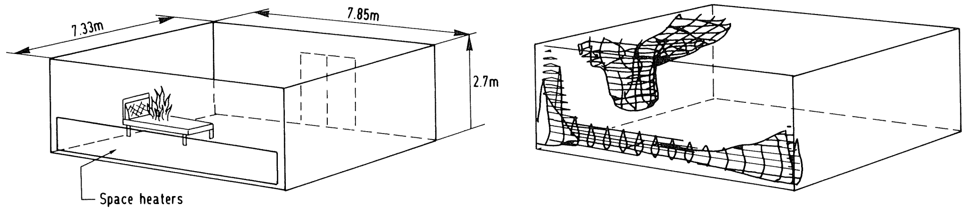
Due to the very vigorous development of information technology during the last years, however, numerical methods are now available, allowing a theoretical analysis of the growth phase of fires. Such analyses are based on two- or three-dimensional heat and mass transport, solving the equations for conservation of mass, momentum and energy for discrete points in the enclosed compartment and are, therefore, commonly referred to as "field models". Material properties and boundary conditions can be defined as functions of temperature, if necessary. In several countries, e.g. U.K. and France, field models are already available [52], [60], [61]. In The Netherlands, both at the Delft University of Technology and at TNO, work in the field is under way [50], [62]. Some idea of what can be is achieved by such models is given in Fig. 11.

It is emphasised that the software necessary for field models is of specialised and complex character. Hence, field models are not likely to be used as a direct design tool. Their benefit lies more in a systematic analysis of fire scenarios, providing the basis for more practice orientated - that is: simplified - models.

Trade-off

The objectives of a fire safety design may, generally, be achieved in several possible ways. To illustrate this, just imagine that, for any functional reason, it is required that a fire should not spread from one compartment to another. This aim can be achieved by any of the following measures:

- to obviate or protect possible ignition sources, in order to prevent a fire from breaking out;



(a) Schematic representation of six-bed hospital ward

(b) The 14°C temperature rise contour, 30 seconds from ignition

Fig. 11. Effect of a slowly growing bedding fire in a hospital.
a. schematic representation of six-bed hospital ward;
b. the 14 °C temperature rise contour, 30 seconds from ignition.

- to install an (automatic) extinguishing device, in order to prevent the fire from growing into a fully developed fire;
- to provide adequate fire resistance of the relevant building components, in order to prevent a fully developed fire from spreading from the fire compartment to adjacent compartments.

The above illustration exemplifies the three main categories of fire safety precautions: fire prevention, operational or active measures and structural or passive measures. The suggestion that the three solutions are interchangable, presupposes that they are equally effective. Generally this will not be so, since each of the solutions will have its specific degree of reliability, which can of course be influenced by (technical) arrangements, such as inspection, good workmanship, etc. Therefore, in practice a combination of fire safety precautions will often be aimed at. Ideally, the fire safety design concept should allow for a certain equivalency of the different design solutions. However, in the traditional concepts - either in The Netherlands and elsewhere - this trade-off is quite impossible. Under certain circumstances this may lead to heavily unbalanced solutions.

The main reason why trade-off is so problematic is that the present concepts of fire safety, and particularly the fire regulations, focus on passive measures, with emphasis on the verification of the requirements rather than on the requirements themselves. Another problem is the deterministic character of these concepts. This does not allow us to define functional criteria on the basis of which the different effects of the various possible solutions can be weighted. For example, how should the reduced probability of flashover due to the installation of a sprinkler system - in deterministic terms - be translated into a reduction of the fire resistance requirements? A probability - based design concept, however, provides criteria for quantifying trade-off in a very logical way [64–66].

The starting point in a probability based design is to define target reliabilities for certain unwanted events, e.g. the spread of fire from one compartment to another. Ideally, the target reliability should be derived on the basis of cost-consequence considerations. The next step is to calculate the actual probability of occurrence of the unwanted event, the so-called failure probability. This will be a function of the various physical processes involved, but also of the anticipated effects of the various active and passive fire safety precautions, and calls for proper modelling, accounting for intrinsic randomness as well as model uncertainties. The design criterion is that the failure probability must not exceed the target reliability. This condition provides a rational framework for trade-off.

For a conceptual approach towards a probabilistic fire safety design, in which also the notion of trade-off is worked out more precisely for structural fire safety, see [66–68].

Expert systems

Due to the rather complex character of the fire safety concept, regulations in this field tend also to be complex. Improvements in this respects are problematic, especially if a more differentiated (=functional) approach is aimed at; see, for example, the above notions on trade-off and probability-based design. Access to the fire safety regulations and design methods therefore is - and will increasingly become - difficult, particularly for those who use it only occasionally. This often leads to misinterpretation and later, when the design is checked by the authorities and is proved to be inconsistent, could have a substantial impact on the building costs. A possible way to overcome this complication is to use expert system technology [69]. In this technology the computer guides - so to speak - the user through the system by posing a series of logical questions. Explanations and help will accompany the questions and conclusions. Extension with a calculation mode (e.g. for the analytical determination of the fire resistance) and/or with a data base including graphical options (e.g. for storage of experimental data) is feasible. To date, at TNO and elsewhere, pilot studies are under way to trace the possibilities of expert system technology applied to fire safety regulations [70], [71]. The results of these studies are likely to be encouraging.

European harmonization

The target date for a free European market is 1992. Removal of the "barriers to trade", constituted by different fire safety concepts for buildings is a declared area of high priority. In the field of fire safety, therefore, many initiatives have been taken to achieve this aim [72], [73]. Some recent developments will briefly be reviewed below. The discussion will be confined to practical (design) aspects. Hence, legislative problems - which do also play an important part - will not be considered.

The removal of trade barriers resulting from differences in fire safety design concepts does not necessarily mean that the level of requirements itself should be harmonized. To arrive at a common European method of assessment with respect to fire protection of buildings will be sufficient. Such a method of assessment should include both fire test procedures and calculation methods. Generally speaking, the harmonization of calculation methods does not cause significant problems because it is normally not difficult to compare the quality of the various models, and adapting a model does not involve great expense. Moreover, many of the calculation models used at present - especially those for determining fire resistance - have been developed in an international context, see, for example [28-33].

Harmonizing the standard fire tests on building components seems, at first glance, also to be an easy task, since these are commonly based on world wide accepted heating conditions, the so-called ISO standard fire. However, in the various countries testing equipment, testing details and testing practice may differ. This is often (used as) an argument to reject foreign test evidence. As a result, building components tested in one country have to be tested again in other countries. Therefore, already some years ago, a document was published on behalf of the Directorate General III of the EEC, in which further details are specified regarding standard fire resistance testing [74]. This document is intended as a guideline for national fire laboratories in homologizing their test procedures and equipment. For reasons as explained earlier, the situation with respect to reaction to fire tests on building materials is much more complicated. Here not even a common basis exists and transferring test results from one national classification system into another is virtually impossible [75]. Due to the complexity of the physical phenomena involved, it may still be many years before a rational solution is found. Therefore, for the time being, consideration must be given to a more pragmatic solution in which the main elements of various national systems are - so to speak - combined into an European assessment method for reaction to fire [76]. In other fields where testing is inevitable - e.g. smoke production, toxicity - harmonization as such is felt to be fairly easy. The reason is simply that such tests have so far been standardized only in a very limited number of countries. As far as smoke production is concerned it is to be noted that an adequate ISO test procedure is available [16].

Finally, one should keep in mind that it is virtually impossible to specify fire test procedures so precisely that differences in interpretation can completely be excluded. In view of European harmonization it is necessary to create an international platform to discuss and evaluate periodically problems of this kind. For this reason the European Group of Official Laboratories for Fire Testing (EGOLF) has been established. The aim of this Group, of which TNO is a member, is to promote interlaboratory acceptance of fire test data.

4 Acknowledgements

In the early sixties the senior author, Witteveen, was encouraged by Ligtenberg to study the behaviour of structures exposed to fire. Most of the ideas conceived by the latter in that period have become reality. Both the present authors are grateful for Ligtenberg's inspiring ideas and support over a period of more than 25 years.

5 References

1. Dezutter, W. P. and M. J. Ryckaert, Een stedelijk bouwvoorschrift uit 1232 tegen brandgevaar (A local building code on fire safety dating from 1232), Catalogus tentoonstelling op en om de bouwwerf, Bruges 1975.
2. Ingberg, S. H., Tests of the Severity of Building Fires, Quarterly of National Fire Protection Association, No. 22, 1928.
3. Fire Test of Brick Joisted Buildings, Quarterly of National Fire Protection Association, No. 22, 1928.
4. Besson, J. and J. P. Fackler, Essais d'Incendie dans des Immeubles Réels a l'Usage d'Habitation, Cahiers du Centre Scientifique et Technique du Batîment, No. 29, Cahier 245, Paris, 1957.
5. Ptchélintzev, A. A., Etude du régime thermique des incendies dans le but de déterminer les limites de stabilité au feu à préscrire pour les éléments de construction, Institut Scientifique Central pour la recherche sur la prévention du feu, Moscow, 1958.
6. Tie, T. T. and J. F. van Sante, Observations During a Fire at Zwolle, Technical Translation No. 935, National Research Council of Canada, Ottawa, 1961.
7. Pettersson, O., Structural Fire Engineering Research Today and Tomorrow, Lund Institute of Technology, Lund, 1966.
8. Kawagoe, K. and T. Sekine, Estimation of Fire Temperature-Time Curve in Rooms, Occasional Reports No. 11 and 17, Japanese Building Research Institute, Tokyo, 1963 and 1964.
9. Ödeen, K., Theoretical Study of Fire Characteristics in Enclosed Spaces, Bulletin 10, Division of Building Construction, Royal Institute of Technology, Stockholm, 1963.
10. Magnusson, S. E. and S. Thelandersson, Temperature-Time Curves for the Complete Process of Fire Development - A Theoretical Study of Wood Fuel Fires in Enclosed Spaces, Acta Polytechnica Scandinavia, Civil Engineering and Building Series, No. 65, 1970.
11. Harmathy, T. Z. and J. R. Mehaffey, Post-flashover Compartment Fires, Fire and Materials, Vol. 7, No. 2, 1983.
12. Babrauskas, V., COMPF2 - A Program for Calculating Post-Flashover Fire Temperatures, Technical Note 991, National Bureau of Standards, Washington, 1979.
13. Bøhm, B., Fully Developed Polyethelene and Wood Compartment Fires with Application to Structural Design, Technical University of Denmark, 1977.
14. Lie, T. T., Een methode om de rookontwikkeling van materialen te meten (A method for determining smoke generation of materials), TNO-report BV-67-6, februari 1967.
15. ASTM E 662-83, Specific optical density of smoke generated by solid materials, 1983.
16. ISO TR 5924, Smoke generated by building products - dual chamber test, to be published in 1988.
17. De proefneming op 12 augustus 1930 - Beschrijving en resultaten der proefnemingen met het gebouw vervaardigd door De Vries Robbe & Co N.V. en N.V. Betondak (The tests on August 12, 1930 - Description and results of the tests in the building erected by De Vries Robbe & Co N.V. and N.V. Betondak), Rotterdam, 1930.
18. Fire Resistance Tests - Elements of Building Construction, International Standard ISO 834, first edition, 1975.
19. Witteveen, J., Brandveiligheid Staalconstructies (Fire Safety of Steelstructures), Stichting Centrum Bouwen in Staal, Rotterdam, 1966.
20. Magnusson, S. E., O. Pettersson and J. Thor, Fire Engineering Design of Steel Structures, Publication 50, Swedish Institute of Steel Construction, Stockholm, 1976.
21. Centre Scientifique et Téchnique du Batîment, Méthode de Prévision par le Calcul du Comportement au Feu des Structures en Béton, Document Téchnique Unifié, Paris, 1980.
22. Lie, T. T., A Method for Assessing the Fire Resistance of laminated Timber Beams and Columns, Canadian Journal of Civil Engineering, No. 4, June 1977.
23. AISI, Fire-Safe Structural Steel - A Design Guide, American Iron and Steel Institute, 1976.
24. Centre Technique Industriel de la Construction Métallique, Méthode de prévision par le calcul du comportement au feu des structures en acier, Construction Métallique, No. 4, Decembre 1976.

25. Twilt, L. and J. Witteveen, Brandveiligheid Staalconstructies (Fire Safety of Steel Structures), Staalcentrum Nederland, Rotterdam, 1985, 1th edition 1980.
26. Schleich, J. B., J. Cl. Dotreppe and J. M. Franssen, Computer Assisted Analysis of the Fire Resistance of Steel and Composite Concrete-Steel Structures (REFAO-CAFIR), C.E.C. Agreement Number No. 7210-SA/502, Final Report, March 1986.
27. Kerstma, J., F. S. K. Bijlaard and L. Twilt, On the Deformation Behaviour of Fire Exposed Steel Beams, TNO-report BI-79-73, 1979.
28. Centre Technique de l'Industrie du Bois, European Code Related to the Determination of the Behaviour of Wooden Building Components Exposed to Fire, Preliminary Draft, November 1980.
29. ECCS-Technical Committee 3, Recommendations for the Fire Safety of Steel Structures: Calculation of the Fire Resistance of Load Bearing Elements and Structural Assemblies Exposed to the Standard Fire, European Convention for Constructional Steelwork, Elsevier, Amsterdam-Oxford-New York, 1983.
30. ECCS-Technical Committee 3, Design Manual on the European Recommendations for the Fire Safety of Steel Structures, European Convention for Constructional Steelwork, Publication No. 35, 1985.
31. Comité Euro-International du Béton, Design of Concrete Structures for Fire Resistance, Appendix to the CEB Model Code, Bulletin d'Information No. 145, Paris, 1984.
32. ECCS-Technical Committee 3, Calculation of the Fire Resistance of Composite Concrete Slabs with Profiled Steel Sheet, European Convention for Constructional Steelwork, Publication No. 32, 1984.
33. ECCS-Technical Committee 3, Calculation of the Fire Resistance of Composite Steel Concrete Columns, European Convention for Constructional Steelwork, to be published in 1988.
34. Calorimeter Bomb Test, Draft ISO recommendation No. 1716, August 1968.
35. Non-combustibility Test for Building Materials, International Standard ISO R 1182, 1970.
36. NEN 3883, Bepaling van de ontbrandbaarheid van bouwmaterialen en hun rookontwikkeling bij brand (Assessment of the contribution to fire propagation of building materials and the optical density of smoke produced by such materials), Nederlands Normalisatie Instituut, Delft, december 1978.
37. BS 476, Part 7, 1987, Fire tests on building materials and building structures - method for classification of the surface spread of flame of building products, 1987.
38. DIN 4102, Teil 1, Brandverhalten von Baustoffen und Bauteilen, 1981.
39. NF P 92-501, Sécurité contre l'incendie bâtiments - essais de réaction au feu des materiaux, 1985.
40. Wakamatsu, T., Calculation Methods for Predicting Smoke Movement in Building Fires and Designing Smoke Control Systems, Fire Standards and Safety, ASTM STP 614, American Society for Testing and Materials, Gaithersburg, 1976.
41. Seeger, P. C., Luft- und Rauchgasstromung in einem Gebäude im Brandfall, V.F.D.B.-Zeitschrift, 26. Jahrgang, August 1977.
42. Majou, A.-M., Smoke Control in Compartmented Buildings, CIB Working Paper, Publication 72, CIB, 1983.
43. Twilt, L. and H. Zorgman, Smoke Problems in Buildings on Fire, International conference NVBC in Amsterdam on January 23–24, 1979, Amsterdam, 1979.
44. Dijk, H. A. J. van, The Movement of Smoke in Buildings on Fire Calculated by Means of a Dynamic Computer Model, Syllabus XXIth International Congress for Building Services Engineering, Berlin, April 1980.
45. Aken, J. A. van, Rookverspreiding in verkeerstunnels bij brand (Smoke Propagation in Traffic Tunnels on Fire), TNO-rapport B-82-455, 1982.
46. Thomas, P. H., P. L. Hinkley and D. L. Simms, Investigations into the flow of hot gases on roof venting, Fire Research Technical Paper No. 7, London HMSO.
47. Thomas, P. H. and P. L. Hinkley, Design of roof venting systems for single storey buildings, Fire Research Technical Paper No. 10, London HMSO.
48. Butcher, E. G. and A. C. Parnell, Smoke control in fire safety design, E. & F. N. Spon, London, 1980.

49. AKEN, J. A. VAN and L. TWILT, Rookverspreiding in grote ruimten (Smoke Propagation in Large Rooms), SBR rapport 141, Rotterdam, 1986.
50. LINTHOUT, S. J. M., Stratificatie van rook in gebouwen bij brand (Stratification of Smoke in Buildings during Fires), TNO-TPD rapport 700.201-1, februari 1978.
51. LEUR, P. H. E. V. D., C. R. KLEIJN and C. J. HOOGENDOORN, Numerical Study of the Stratified Smoke Flow in a Corridor: Full Scale Calculations, Private Communication, to be published in Fire Safety Journal.
52. COX, G. and S. KUMAR, Field Modelling of Fire in Forced Ventilated Enclosures, Combustion Science and Technology, Vol. 52, 1987.
53. AKEN, J. A. VAN, Rookverspreiding in gebouwen bij brand: Illustratie van een rekenkundige benadering voor een drietal gebouwtypen (Smoke movement in buildings on fire: Illustration of an analytical method for three types of buildings), Stichting Bouwresearch, Rapport B 29-3, Rotterdam, 1984.
54. Model Bouwverordening (Model Fire Code), Vereniging van Nederlandse Gemeenten, Den Haag, december 1978.
55. WITTEVEEN, J. and L. TWILT, Principles in Fire Engineering Design, Fire Safety in Constructional Steelwork, Chapter I, European Convention for Constructional Steelwork, 1974.
56. TWILT, L., Fire regulations in The Netherlands, International Conference on European Fire Regulations, Thessaloniki, June 1987.
57. WITTEVEEN, J., A Systematic Approach Towards Improved Methods of Structural Fire Engineering Design, Proceedings of the 6th International Fire Protection Seminar organized by VFDB, Karlsruhe, 1982.
58. Final draft NEN 3886, 3887, 3888, 3889, Rekenkundige bepaling van de brandwerendheid van bouwdelen (Analytical Determination of the Fire Resistance of Building Components Exposed to Fire, Nederlands Normalisatie Instituut, to be published in 1988.
59. NOORMAN, TH. M. and R. J. M. VAN MIERLO, Rookwering in vluchtwegen door overdrukventilatie (Smoke Control in Escape Routes by Pressurizing), SBR rapport, to be published in 1988.
60. CURTAT, M. R. and X. E. BODART, Simple and Not So Simple Models for Compartment Fires, Fire Safety Science-Proceedings of the first International Symposium, International Association for Fire Safety Science, Washington, 1985.
61. KUMAR, S., Mathematical Modelling of Natural Convection in Fire - A State of the Art Review of the Field Modelling of Variable Density Turbulent Flow, Fire and Materials, Vol. 7, No. 1, 1983.
62. MIERLO, R. J. M. VAN and A. D. LEMAIRE, Analytische modelvorming voor zich ontwikkelende branden - rapportage van de 1ste fase (Analytical modelling of the growth period of fires - report on the 1th phase), TNO-IBBC rapport BI-87-54, 1987.
63. MOSS, J. B., G. COX and S. KUMAR, Laminar Flamelet Models of Fire - The Prospect, Proceedings of the workshop on fundamental aspects of polymer flammability, Fire Research Station, Borehamwood, April 1987.
64. PETTERSSON, O., Reliability Based Design of Fire Exposed Concrete Structures, Contemporary European Concrete Research, Stockholm, June 1981.
65. SNEIDER, U., D. BUB and M. KERSKEN-BRADLEY, Structural Fire Protection Levels for Industrial Buildings, Fall Convention, American Concrete Institute, San Juan, Puerto Rico, 1980.
66. CIB W14, A Conceptual Approach Towards a Probability Based Design Guide on Structural Fire Safety, Fire Safety Journal, 6 (1), 1983.
67. CIB W14, Design Guide Structural Fire Safety, Fire Safety Journal, 10 (2), 1986.
68. TWILT, L. and A. C. W. M. VROUWENVELDER, CIB-Concept for Probability Based Structural Fire Safety Design, Fire Safety Science-Proceedings of the first International Symposium, International Association for Fire Safety Science, Washington, 1985.
69. WAGNER, D. M., Expert Systems and the Construction Industry, CICA Publication, Cambridge, 1984.
70. OEY, K. H. and E. PASSCHIER, BRAM: An Expert Systems Approach for Codes of Practice, TNO report BI-87-69, 1987.

71. SMITH, C., Cahier des Charges Préliminaire du Systeme Expert en Sécurité, Centre Technique et Industriël de la Construction Métallique, Federation Nationale du Bâtiment, septembre 1987.
72. WITTEVEEN, J. and L. TWILT, International Standardization: Advantages, Progress, and Problems, Fire Standards and Safety, ASTM STP 614, American Society for Testing and Materials, Gaithersburg, 1976.
73. European Fire Regulations, International Conference, hold in Thessaloniki on June 29–30, 1987.
74. DEKKER, J., M. KLINGELHÖFER and P. VANDEVELDE, Testing and classification of the resistance to fire of structural building components, Commission of the European Communities, Directorate-General, Internal Market and Industrial Affairs, EUR 8750 EN, Brussels, 1984.
75. BLACHÈRE, G., H. TEPHANY et Y. TROTTEIN, A Propos des Essais de Reaction au Feu dans la C.E.E., Paris, 1985.
76. Commission of the European Communities, Draft Proposal for Council Directive: Concerning the reconcilation of the legislative, regulatory and administrative provisions of the Member States relating to the evaluation and classification of the fire performance of the construction products, Private Communication, 1986.