The Swedish Case Study, Different Fire Safety Design Methods Applied on a High Rise Building

Jönsson, Robert; Lundin, Johan

1998

LUND UNIVERSITY

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

Brandteknik
Lunds Tekniska Högskola
Lunds Universitet

Department of Fire Safety Engineering
Lund Institute of Technology
Lund University

Report 3099

THE SWEDISH CASE STUDY

DIFFERENT FIRE SAFETY DESIGN METHODS APPLIED ON A HIGH RISE BUILDING.

Robert Jönsson
Johan Lundin

Dept of Fire Safety Engineering
Lund University, SWEDEN
http://www.brand.lth.se/english/

Presented at the Second International Conference on Performance-Based Codes and Fire Safety Design Methods, Maui, USA, 5-9 May 1998.

The report has been financed by the Swedish Fire Research Board (Brandforsk) and the Development Fund of the Swedish Construction Industry (SBUF).

ISSN 1102-8246
ISRN LUTVDG/TVBB—3099--SE

Keywords:
Fire safety, evacuation, building regulation, high rise building, risk analysis, fire safety engineering, risk based verification, risk based design.

Abstract:
The present report concerns a performance-based fire safety analysis and design of a high-rise building. The resulting fire safety recommendations are compared with those specified by acceptable solutions in terms of the earlier prescriptive building code. The respective risk to life resulting from the analyses is compared and discussed. The benefit and need of using a risk based verification method as a complement to a deterministic fire safety engineering method is demonstrated. The cost-effectiveness of different solutions is also demonstrated.

Layout/Figures/Diagrams: Johan Lundin and Robert Jönsson

THE SWEDISH CASE STUDY
DIFFERENT FIRE SAFETY DESIGN METHODS
APPLIED ON A HIGH RISE BUILDING.

Robert Jönsson
Johan Lundin

Dept of Fire Safety Engineering
Lund University, SWEDEN
http://www.brand.lth.se/english/

Presented at the Second International Conference on Performance-Based Codes and Fire Safety Design Methods, Maui, USA, 5-9 May 1998.

CONTENTS

CONTENTS 6

ACKNOWLEDGEMENT 8

SUMMARY 9

1. INTRODUCTION 11

2. SWEDISH BUILDING REGULATIONS 13

3. DESIGN METHODS 15
3.1 Standard Method 15
3.2 Alternative standard method 16
3.3 Fire safety Engineering methods 16
3.4 Risk based method 17
3.4.1 Risk based verification method 17
3.4.2 Risk based design method 20
3.5 Uncertainty analysis 21

4. DESCRIPTION OF THE BUILDING AND DESIGN ALTERNATIVES 23
4.1 Architectural design 23
4.2 Design according to the standard method 24
4.2.1 Fire resistance classification 24
4.2.2 Escape routes 24
4.2.3 Fire compartment subdivision 25
4.2.4 Installations 26
4.2.5 HVAC-systems 27
4.3 Design according to the alternative standard method 27
4.4 Design according to the fire safety engineering method 27

5. ENGINEERING CALCULATIONS 29
5.1 Design fire scenarios 29
5.2 Evacuation time 30
5.2.1 Detection and reaction times 30
5.2.2 Travel time 30
5.3 Verification of design alternatives 32
5.4 Reliability of technical systems 33
5.5 Risk comparison 34

6. RELATIVE FINANCIAL COMPARISON 36
6.1 General assumptions: 36
6.2 Specific costs 36
6.3 Design solution costs 36

7. DESIGN OF THE LOAD BEARING STRUCTURE 37
7.1 Introduction 37
7.2 Building code requirements 37
7.3 Load bearing structure and partitions 38
7.4 Sample calculation 38

8. DISCUSSION AND CONCLUSIONS 40

9. REFERENCES 43

APPENDIX 1, SWEDISH BUILDING REGULATIONS (BBR94, BKR94) 48
Parts of BBR 94 48
Parts of BKR94 61

APPENDIX 2, DRAWINGS 65

APPENDIX 3, FIRE SAFETY DOCUMENTATION 68
Inspection plan in accordance with the Planning and Building Act (PBL) 69

APPENDIX 4, DESCRIPTION OF COMPUTER MODELS. 71
CFAST 71
Detact-t^2 71
Simulex 71

APPENDIX 5, MODELLING THE DESIGN FIRE SCENARIO. 73
General conditions and assumptions 73
Design Fire 74
Sensitivity analysis 75
Sprinkler activation time 75
Smoke alarm activation time 75

APPENDIX 6, EVACUATION CALCULATIONS 77
General conditions and assumptions 77
Evacuation of office floor 77

APPENDIX 7, RELIABILITY OF TECHNICAL SYSTEMS 80

APPENDIX 8, EVENT TREES OF THE DESIGN ALTERNATIVES 82

ACKNOWLEDGEMENT

The authors of this report would like to thank Dr Håkan Frantzich for his invaluable contribution through his dissertation (Frantzich 1998).

Jan Bergfelt Architect, SYDARK AB, to whom we are grateful, has prepared architectural drawings.

We are also grateful to the sponsorship given by Brandforsk, The Swedish Fire Research Board, and leading fire consultant companies in Sweden:

Bengt Dahlgren AB, Per-Anders Marberg
Brandgruppen AB, Olle Norrby
Säkerhetspartner AB, Mikael Bergfelt

The Construction Company NCC is also acknowledged for providing us with information about construction costs.

SUMMARY

On behalf of SFPE in conjunction with the Second International Conference on Performance-Based Codes and Fire Safety Design Methods, Maui, USA, 5-9 May 1998, a case study was carried out, based on Swedish conditions, on the subject of fire safety.

The present report concerns a performance-based design and fire safety analysis for a high-rise building, the resulting fire safety recommendations being compared with those specified by acceptable solutions in terms of the earlier prescriptive building code. The respective risk to life resulting from the analysis is compared and discussed in chapter 5. The cost-effectiveness of different design solutions is shown in chapter 6. Three different design methods are identified as possible approaches to deal with design according to performance based regulations.

The design process is performed on three levels, where one is the former prescriptive solution, which is still valid.

- **Standard method**
  Simple handbook solution, i.e. using former prescriptive regulations.
- **Fire safety engineering method**
  Calculation on sublevel, for example, evaluating escape time margin.
- **Risk based verification method**
  Evaluation on system level with risk analysis, i.e. performing a quantitative risk assessment QRA.

The performance based design is based on a design in accordance with traditional acceptable solutions, i.e. former prescriptive code solutions. With this as a starting point, three alternative designs are made with the fire safety engineering method, limited to achieve the life safety goal. The main emphasis in the alternative designs is the number of staircases needed for safe evacuation. This has been evaluated together with different combinations of sprinkler system, detection system and alarm systems. No consideration is taken to the rescue service and its ability.

A quantitative risk assessment is then carried out to quantify the risk associated with the different design solutions, using a risk based verification method. The designs are evaluated by comparing the risk levels and also by simple comparisons of their production costs. Acceptable safety can be ensured either by comparing the proposed design with accepted solutions or with tolerable levels of risk. In this case study the acceptable level of risk is the same as the risk a design evaluated for according to the former prescriptive code would have.

It was found that only one of the designs according to the fire safety engineering method provided acceptable safety in case of fire and it also proved to be cost effective. The right choice of solution, using the fire safety engineering method, could only be made by using a risk based verification method in the evaluation process. This was also one of the findings from a recently finished Swedish study (Boverket 1997), which conlcuded that misuse of the fire safety engineering method can lead to unsafe buildings. This clearly shows the benefit and need of using a risk based verification method as a complement to a deterministic engineering method.

No final judgement is made of which solution to chose for the final design. A different design solution might have been obtained if this had been a real project where compromises have to be done with other engineering disciplines, and if more reliable data for calculating the construction costs were available. This means that some of the suggested solutions might not be realistic, but the method of relative comparisons is still valid and useful in “real” projects.

The important difference between the fire safety engineering method and the risk based method is when decisions are made. Whether a design solution should be accepted or rejected is not exclusively based on the performance of the system when everything works accordingly. It will be based on that the consequences will be lower than a certain acceptable limit, taking into account that the conditions specifying how the safety systems will interact with the surrounding are not constant. The decision is based on more information than just out of one single design scenario.

The following conclusions could be drawn from this report:

- The use of a fire safety engineering method must be done carefully, since misuse can easily give the wrong impression that the building is safe enough.

- a risk based verification method or design method is a necessity if consideration is taken to reliability of different components, i.e. design is carried out on system level.

- the risk based verification method presented and used in this report is suitable for relative ranking of different design solutions.

- when using a fire safety engineering method in combination with a risk based verification method the cost effectiveness is clearly demonstrated.

- one weakness of the methods applied is the lack of reliable data to be used in the calculations and it is obvious that more work has to be done both in collecting and structuring data.

- using a risk based verification method as a complement takes much longer time to perform than simple engineering methods but it is a necessity and it is also economically defendable in a building of this type.

1. INTRODUCTION

In a recently finished study by the National Board of Housing, Building and Planning in Sweden (Boverket 1997) the use of the new performance-based building code was evaluated. Two actual buildings were studied, both according to the new and old regulations. The former code (NR 1988) was a traditional prescriptive building code. The evaluation showed that the current regulations are not applied in a satisfactory manner and that the knowledge available is not used to that extent that should be expected. This conclusion is valid both for the technical solutions chosen, the verification, the documentation, the use of engineering methods and for the quality control measures before and during construction. The uncertainty whether or not a building meets the performance criteria and can be regarded as reasonably safe has increased due to misusing of fire safety engineering methods. From a questionnaire in the finished study it was concluded that the people involved in the process have much to low competence in understanding the real nature of fire safety engineering.

The present report concerns a performance-based design and fire safety analysis for a high-rise building, the resulting fire safety recommendations being compared with those specified by acceptable solutions in terms of the earlier prescriptive building code. The respective risk to life resulting from the analysis is compared and discussed in chapter 5. The cost-effectiveness of different design solutions is shown in chapter 6. As an addition examples of structural design is demonstrated in chapter 7.

Since it is not customary to erect 40-story buildings in Sweden, the solutions acceptable in terms of the building code are not valid for that height. Thus, the building used in this case study is 20 stories in height, even though the code is not appropriate for that type either but some experiences exists for buildings of that height. The architectural design is shown in appendix 2 and the building description in chapter 4.1.

The solutions and engineering calculations presented are not complete. They simply exemplify how some of the important fire prevention steps could be taken.

The report is based on a design in accordance with traditional acceptable solutions, denoted here as the standard method. The procedures used in the standard method are described in chapter 3.1 and the design solution using this method is described in chapter 4.2. With this as a starting point, alternative methods are used to produce different design solutions. The different design methods that are available are summarised in chapter 3 and their suggested solutions are described in chapter 4. The main emphasis in the suggested solutions is the number of staircases needed for safe evacuation, which is believed were the largest savings could be made. In this report only quantitative aspects have been considered and only those worth while considering by the use of engineering calculations. Many other aspects are still and will still be taken into account by using acceptable solutions. Some measures of improving the fire safety could be introduced without the benefits being able to be verified by engineering calculations. One such example is pressurising the staircases.

The alternative design methods available to provide different solutions are:

- **Alternative standard method** (chapter 3.2 and its design solution in chapter 4.3)
- **Fire safety engineering methods** (chapter 3.3 and its design solutions in chapter 4.4)
- **Risk based verification method** (described in chapter 3.4.1)
- **Risk based design method** (not available in this report, described in chapter 3.4.2)

The risk based verification method is first used to evaluate the different design solutions produced by the standard methods and the fire safety engineering method. Three different solutions were proposed by using the fire safety engineering method. In the evaluation process the risk based verification method is then used to further improve a given solution, e.g. the risk based verification method is used for design purposes.

The fire safety analysis and design should meet the following fire and life safety goals set by the building code and the requirements of the building owner:

1. Safeguard occupants from injury due to fire until such time as they reach a safe place. (This may include self-relocation to a safe place within the building, self-evacuation to a safe place outside of the building, evacuation with assistance from the fire service, or any combination of the above.)

2. Limit flame spread and thermal damage to the floor of fire origin, and limit non-thermal damage to the fire floor and one floor above.

3. Provide sufficient structural stability to meet goal 1 and 2 above.

This report is primarily done to achieve safety goal number 1, safeguarding occupants. The evacuation strategy follows the recommendation from the standard method. No discussion is made on how relevant the strategy of evacuating the fire floor and the two floors above and below it is, and no consideration is taken to the interaction and possibilities of the rescue service. If the alarm procedure of evacuating the five floors does not work for the non-fire floors, this has not been taken into account, nor has the possible spread of fire beyond the fire compartment of fire origin.

The evaluation by the risk based verification method is used to evaluate the quantitative risk on one floor. Other safety measures both quantitative and qualitative are taken care of by using the solution obtained in the standard method in all other solutions.

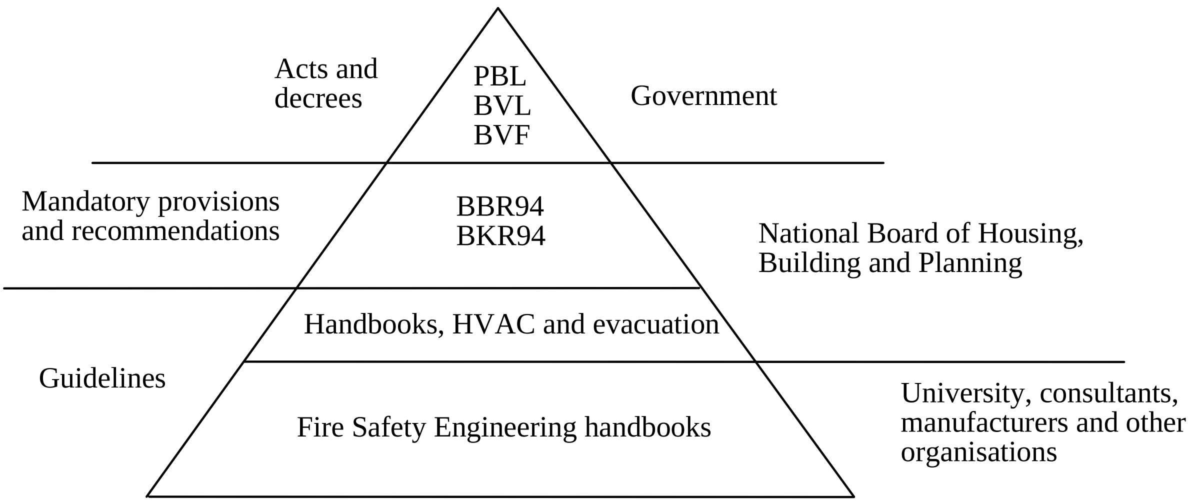
2. SWEDISH BUILDING REGULATIONS

Sweden has since 1994 had performance-based building regulations. In some areas in fire safety this process started as early as 1967. with permitting application of an analytical design of structural elements, based on a natural compartment fire concept.

The Swedish authorities continued their efforts towards fire safety engineering and approved new design documents in 1974 (Pettersson, et al) and 1978 (Pettersson and Öden) for loadbearing and separating structures. This was made possible through extensive research by Magnusson, 1974 and Pettersson and Magnusson, 1978.

The performance-based regulations are in line with the decision made by the Parliament in 1985, to use more scientific based solutions in building fire safety design and not rely so much on rule of thumb and old experiences from building fires.

At the same time there has been a change in the Planning and Building Act were the building owner now has sole responsibility in proving that the building complies with the regulations. This means that the owner has to have the knowledge and experience within his project team. He can no longer leave the fire safety to be decided and/or checked by local authority, which previously used to be the fire service. There is, however one possibility for the local authorities to get some control over the technical solutions and that is by third part control. This can be asked for when the local authority does not believe in the competence of the engineers involved, and when they know from experience that a suggested design is complicated. The Swedish system describing the legal structure and who is responsible for producing different levels of publications are described in figure 1.



PBL - Planning and Building Act (1987:10)
BVL - Act (1994:847) on Technical Requirements for Construction Works etc
BVF - Decree (1994:1215) on Technical Requirements for Construction Works etc
BBR94 - Building Regulations (BFS 1993:57 with amendments BFS 1995:65)
BKR94 - Design Regulations (BFS 1993:58 with amendments BFS 1995:18)

Figure 1. The relationship between governmental agencies, private companies on one hand and different rules, regulations and recommendations on the other hand.

One of the major improvements in the new building code, is the requirement of fire safety documentation. The building owner shall, according to section 5:12 in BBR 94 (1994) (see appendix 1), produce a detailed description about the fire safety design in the building and special care has to be taken if fire safety engineering methods are used in the design. An instruction of what should be included in documentation is shown in appendix 3. The extent of the documentation depends on which design method used.

The main objective is that the building should be constructed so that the outbreak of fire could be prevented and the spread of fire and smoke in the building limited. Persons in the building should be able to escape safely from the building or be rescued in some other way. Safe evacuation of the occupants may be achieved by early warning of an incident, clear instructions, safe escape routes and if the emergency would be a fire, by initial control of the fire size. Safe escape routes as well as the initial control of the fire size may primarily be achieved by fire compartmentation. The compartmentation for preventing fire spread should be done according to the minimum requirements and no extra attention has been paid to minimise the possible property damage.

In general, it is specified in the Swedish building regulations that fire protection devices should have instructions for function checking, and the necessary maintenance (see appendix 3). Since there are no specific requirements in the regulations, the manufacturer's recommendations are normally followed. There is no formal inspection body, so it is the responsibility of the building owner. The local authority could check this, but it is seldom done.

The regulations (set by the insurance companies and recommended in the building code for the fire alarm installations) for alarms and sprinklers (e.g. the NFPA standards) specify how, when and by whom inspection and maintenance of alarm and sprinkler installations are carried out.

Specially certified persons shall check the ventilation system regularly in Sweden. This inspection is intended for the benefit of health and the environment, but the fire protection of the installations is normally checked at the same time.

It is the responsibility of the employer, according to Swedish law, to ensure that their personnel are well acquainted with the fire and personnel protection in the workplace. There is no external inspection body to ensure compliance with this law.

3. DESIGN METHODS

3.1 STANDARD METHOD

In the former prescriptive building code (NR 1988) detailed solutions to most fire safety problems for simple buildings were given. The standard method, which is the traditional approach, was developed on the basis of these detailed solutions together with detailed instructions from different handbooks. No engineering calculations, except for load-bearing structures, are used and the knowledge required is minor. Technical systems (e.g. sprinkler, fire alarm etc.) are not introduced unless specified in the detailed solutions. The standard method is still used today in the majority of design applications, and most of the earlier accepted solutions meet the performance requirements in the new code (BBR94, 1994).

The standard method is based on the following assumptions:

- The action of the fire brigade would generally be expected within the normal attendance time (10 minutes). If not, improvements in fire safety are sometimes needed.

- Safe distances, fire brigade interaction and specified load bearing capacity take care of the threat of fire spreading to neighbouring buildings.

- Safe evacuation is primarily achieved by requiring at least two independent escape routes and by fire compartmentation limiting the travel distances to and within the escape routes. Sometimes, one escape route is enough, although the escape route must then be constructed with higher fire safety. In buildings where the fire brigade's ladder equipment can be used, windows can sometimes be considered escape routes.

- The design of the required exit widths is done according to prescribed occupant loads and from the assumption that 150 persons calls for 1 meter clear door width. The case in which one escape route is blocked should also be considered. A 1 meter width is needed then for 300 persons.

- Buildings taller than 16 floors are usually not built in Sweden, not being a part of our building tradition. This is an important limitation to the use of the standard method.

- Sprinkler systems are traditionally not used in this type of building, but are gradually being introduced more often. The alternative standard method can then be employed as described in chapter 3.2.

- In an international comparison, the load bearing and fire compartmentation requirements, based on a long tradition in Sweden, might appear to be low. If an automatic sprinkler system is installed or if the fire brigade can put out the fire within 60 minutes, the highest requirement is 90 minutes (R90) independent of the fire load density.

3.2 ALTERNATIVE STANDARD METHOD

From the standard method a lot of alternatives were developed as acceptable solutions. Either based on praxis, on different types of engineering calculations or on recommendations written in the building code. These alternatives can be found in handbooks and are widely accepted. In this method alternative solutions involving use of various technical systems are presented and applied. If a technical system is introduced as a trade-off, it should result in the same safety level, since the original solution and the overall safety level need to be maintained. In some trade-offs seen as acceptable, however, this is not always the case. Some trade-offs, in fact, are made without any justification being given. Another matter to consider is that the two systems compared should have the same order of reliability. Normally, no consideration is given to this fact. This may lead to different safety levels.

3.3 FIRE SAFETY ENGINEERING METHODS

This method is normally used on a sub-system level to evaluate trade-offs from the standard method, but can also be used to verify that specific objectives in the code is fulfilled. Marberg et al. (1998) exemplifies the use of this method in a practical sense in a case study presented at the fire International Conference on Performance-Based Codes and Fire Safety Design Methods.

The life safety can be quantified as an escape time margin, according to (Magnusson et al. 1995, Frantzich 1998). The escape time margin is the difference between time before conditions in the building becomes critical and the time it takes for people to evacuate the building. The following relationship can be said to hold:

$$M = t_{critical} - t_{evacuation} \qquad \text{(design equation)}$$

where M denotes the evacuation margin, $t_{critical}$ denotes the time available, i.e. the time elapsing until the critical conditions have been reached, and $t_{evacuation}$ the evacuation time, i.e. the time evacuation would require.

The evacuation time can be described in terms of three separate variables:

$$t_{evacuation} = t_{detection} + t_{reaction} + t_{travel}$$

The detection time is either computed or assumed, depending largely on whether or not there is an automatic detection system that activates.

The reaction time involves all actions of the people before beginning to move to a safe location. It is not at all unusual for some time to elapse before the evacuation itself begins. Other activities that may occur include those of attempts being made to extinguish the fire or to find out what has happened, as well as people first completing something they are in the process of doing. In some handbooks reaction time is divided into response time and recognition time.

The travel time is estimated on the basis of such matters as the number of persons involved, the width of doors, passageways and the like and the distance necessary to be in a safe place. It is normally assumed that people can be at many different locations in the building, not simply at the place where the fire breaks out. It is relevant to consider how evacuation can be affected by the presence of other persons not directly affected by the fire.

In this method (BSI 1997, Jönsson et al. 1994, ISO 1997,Fire Engineering Design Guide 1994, Fire Engineering Guideline 1996) deterministic values are used in the design equation. No consideration is taken of system reliability. It is assumed to be a safe design if the evacuation margin exceeds zero. Normally, only a few different scenarios are studied. The design parameters used, such as the design fire growth rate, are chosen in a somewhat conservative way. The choice made is a likely value chosen as being somewhat on the safe side.

3.4 RISK BASED METHOD

3.4.1 Risk based verification method

This is generally called a quantitative risk assessment method (QRA) and can be used in design if the acceptable risk level is known. Since it is not known, one way to estimate an acceptable level is to choose the risk level of a prescriptive solution. That means that first the prescriptive solution has to be done and evaluated with QRA, then some fire safety engineering design solution has to be performed in order to assess the fire safety in the building adequately. In a QRA account is taken of the fact that the safety devices might fail to function. What consequences would it have if the sprinkler system failed to work or the smoke detector failed to respond? What would happen if a fire broke out and both devices failed to function? These questions could be answered when comparing the risk profiles for the different solutions.

The problem with this approach is that the safety is compared with traditional existing design methods, i.e. the prescriptive method. One can argue that using this type of methods are no better than using simple prescriptive methods but it is still a step forward from using prescriptive regulations as the risk is quantified and thereby known. In addition using the QRA enables the designer to judge the benefit from using installations, which are not covered in the prescriptive solution. So, comparing design alternatives can be used but the comparison is only relative and not absolute in terms of risk. It is normally assumed in this type of comparisons that the probability of a fire occurring (P_{fire}), is the same in all the alternatives. There is still lack of knowledge about correlation between P_{fire} and different fire safety precaution, for example education or the design solution itself. Analysis of P_{fire} is therefor not done in the comparison. The comparison is done on the basis that fire has occurred.

The method performed is very simple in its conception and has recently been used in a study by the National Board of Housing, Building and Planning in Sweden to evaluate the new performance-based building code (Boverket 1997). A number of initial events that could cause a fire are identified. These scenarios vary, depending on such factors as the location of the fire, access to the site, and access to inflammable material. The attempt is made to choose scenarios that differ in both their structure and in their consequences. For each scenario, different events are considered, defined for the safety devices as the device's functioning properly or failing. To facilitate work with the different sub scenarios, use is made of an event-tree technique. In an event-tree, the traditional engineering method is only described as a single event and in terms of everything functioning properly.

The analysis involves studying the different scenarios and examining the various possible consequences and the probability of occurrence of each. On the basis of the information this provides, two simple measures of risk are derived, producing a means of comparison. These two measures are a risk profile and an average risk.

For each sub scenario, both the consequences and the probabilities must be known. The question is ‘How can this information be of any use when making decisions related to fire safety engineering?’ There are different ways of describing or defining risk (Magnusson et al. 1994; 1995, IAEA 1989, CPQRA 1989 and Frantzich 1998). The most usual way is to present the probabilities and the consequences graphically in a so-called F N diagram. An F N curve (Frequency Number Curve) indicates at each point on the curve the probability that the consequences will be worse than a certain designated level, the latter normally defined in terms of a certain number of deaths. Since in the report here what is involved is not deaths but is rather simply the state of being a victim of the fire (being exposed to critical conditions), the term ”risk profile” instead of ”F N curve” is employed. ”Risk profile” is a more general term, one that encompasses the F N curve.

The risk profile is a step-wise function, showing an increase left-to-right in the seriousness of the consequences. A risk profile indicates the probability that a fire will have the same or more severe consequences than the x-value. Figure 2 indicates schematically how a simple scenario can be structured with the help of an event tree and the corresponding results of a risk profile. Note that the probability of each alternative sub scenario is represented by the height of the curve.

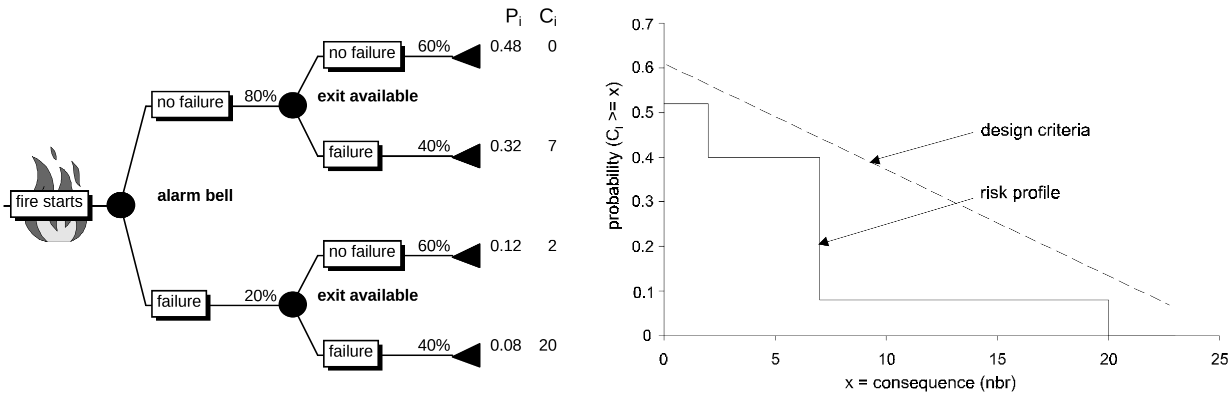


Figure 2. Example of an event-tree and a risk profile. The dotted line is the limit for an acceptable design.

The intersection of the curve with the vertical axis is located at a point representing the sum of the probabilities of those sub scenarios that causes a consequence of greater than 0 ($\sum P_{i,\, C_i>0}$), which is a measure of individual risk. If each of the alternative sub scenarios in the event tree results in one or more persons failing to evacuate, the intersection will be at 1.0, which means that in case of a fire occurring at least one person would be affected by critical conditions every time. Since what is of interest is simply to compare the effects of different designs, the probability of a fire is coming about is not dealt with here. That probability is assumed to be the same in all cases. Otherwise, one would need to multiply the values on the vertical axis by the probability that the scenario of fire itself will occur. A risk profile is interpreted in such a way that those estimates located closer to the lower left-hand corner of the profile are regarded as being more safe.

It is by no means obvious in some cases, which of two risk profiles that is better than the other is. If the two curves cross, the matter cannot be determined in any simple, direct way, other means being called for. The contents of an entire risk profile can be used to obtain a single figure, that of average risk, providing a means of risk assessment parallel to that of the risk profile. For each alternative scenario, the product of the probability and the consequence is obtained, the sum of these products representing the average risk. The average risk indicates the average number of persons that is exposed to critical conditions during a fire.

If there are no rules or regulations concerning acceptable risk and if neither the risk profile nor the average risk can provide a satisfactory means of comparing the risk, a qualitative analysis of risk can serve as a last resort. The appearance of different risk profiles can be studied and a general assessment is made of their acceptability. Problems can be encountered when one or more of the alternative scenarios involves very serious consequences or when the probability is very high of at least some non-zero consequence occurring. Graphically, this appears as a tendency of the risk profile to extend far along either of the two axes in the diagram, a tendency which, if pronounced, can be regarded as unacceptable. This is typically the case when the amount of fire compartmentation is traded off against a sprinkler system without considering the effects.

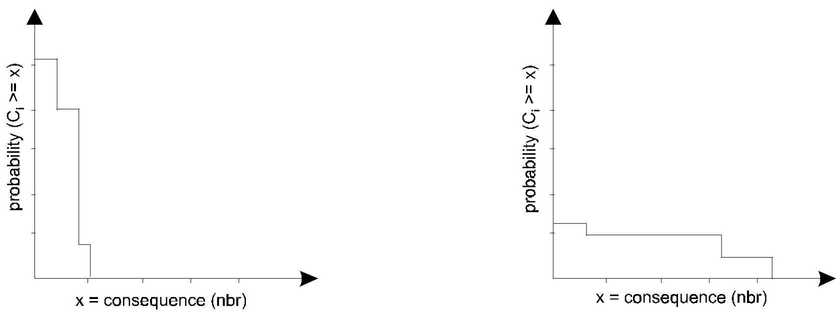


Figure 3. Risk profiles with the same average risk but differing in their characterisation of the risk.

From the standpoint of society, it is normally easier to accept small negative consequences that occur frequently than very serious ones that occur seldom, even if the average loss is the same. In cases in which the criteria for acceptable risk are specified, such as in the building of large chemical factories in the Netherlands, the line of reasoning just presented can be expressed as a risk profile. A line running left to right indicating the maximal level of risk that can be accepted is incorporated into a risk profile, figure 2. Any risk profile that at no point exceeds this level is regarded as acceptable. If, in contrast, a curve exceeds this level at some point, it is considered not to be acceptable and appropriate measures are taken. Often, two separate lines of this sort are drawn, one above the other, measures to reduce risk being generally seen as appropriate for results that fall between these two lines. This is to provide a certain degree of flexibility, since some measures to reduce risk can be more expensive than others can. Thus, one may regard it as temporarily acceptable for a risk profile to partly lie within this intermediate zone (Räddningsverket 1997).

The level of risk found varies considerably among different buildings all erected in accordance with the former prescriptive Swedish building code (NR). Kristiánsson (1997) reported on the fire hazards persons were exposed to in different buildings, all of them constructed in accordance with building regulations. Kristiánsson draws the following conclusions.

- The safety level for persons in buildings that conformed completely to the prescriptive building code was found to vary greatly with a probability of failure varying between 0 and 90 % given that a fire occurs.
- In small rooms in which people assemble, the fire-spread factor is very important.
- The speed with which fire spreads is of greater importance in buildings without a sprinkler or an automatic fire alarm than in buildings having a protective system of this sort.
- Personal safety in rooms where people assemble increases as the size of the floor area and the height of the ceiling increase.
- Large rooms in which people assemble and which have a sprinkler tend to possess a high degree of safety.
- Having properly functioning, automatically-closing doors is extremely important for the safety of persons in hotels.

Accordingly, it can be said that no clearly defined level of fire safety inside of buildings is presently maintained.

Similar investigations have been carried out in buildings where people assemble, as well as in hotels and hospital wards (Magnusson et al 1995, Frantzich 1996 and Frantzich 1997).

Uncertainty regarding the data has not been dealt with thus far. Each of the variables employed in assessing probabilities and consequences is often chosen and examined separately. Although this is the usual approach in carrying out a simple risk analysis, there tends to be considerable uncertainty regarding some variables, such as how a fire would tend to develop. Many other variables may be relevant.

3.4.2 Risk based design method

Safety can be ensured either by comparing the proposed design with accepted solutions as described in the previous chapter or with tolerable levels of risk.

Comparing the design solution with a defined level of risk the designer can use two different approaches:

- Evaluation on system level, i.e. performing a QRA (see chapter 3.4.1)
- Use of design values based on defined risk in deterministic equations.

The QRA method for this situation is the same as described in the previous chapter. The difference lies in that there is a defined risk level available. This defined risk level can be in the form of a limit line (design criteria) in the F N diagram in figure 2.

Tolerable risk levels have been developed for some large infrastructures in a number of countries. The tolerable risk can be defined as a limit line in the F N diagram, usually together with a grey zone in which the risk is tolerable but should preferably be decreased. The curve can also be used to choose a design alternative among similar, with equal risk, but which are associated with different costs. The fire safety community have not yet reached this position for fire safety design.

The second method based on defined level of risk operates with design values, which have been derived from a defined level of risk. Using these values in a deterministic equation leads to results, which are on condition of the initially defined risk level. The designer does not have to bother with risk analysis, as the risk is included in the design values. This is common practice when designing load bearing structures for normal loads.

The method is based on the First Order Second Moment (FOSM) reliability index β method (Magnusson et al., 1994 1995). The reliability index is used to determine the probability that the escape time margin will be negative and is thus a measure of safety or risk. Consideration is taken of variation in the variables studied (i.e. uncertainties). The FOSM method can simply be applied to a single building and used to verify safety. But deriving design values based on the FOSM method is performed in the opposite manner. First, the target risk, in terms of β, is defined. Then the design values are derived with the constraint of meeting the target risk. In addition, these design values must also be valid for a class of buildings and not just one single building.

The case study does not involve use of this method, since design values based on a specified level of risk have not yet been derived. Procedures for such a work are available (Frantzich, 1998) and work are performed to find such design values.

3.5 UNCERTAINTY ANALYSIS

To be able to compute the different times found in the design equation, it is necessary to have access to data of different kinds. Some of the variables involved are simple to obtain and do not change once the characteristics of the building have been specified. Variables that are affected by ongoing activities or that vary over time are more difficult to deal with.

In current handbooks no recommended or design values are suggested which takes into account the uncertainties or their variation. In a risk based method the uncertainty is taken account of in computations concerned with the risk and the probabilities involved. The uncertainty can reflect either ignorance regarding the true size of the variable or normal variation to which the variable is subject. By the latter is meant variation of a random character that cannot be predicted. An example of a variable showing variation of this sort is the probability of rain on the day exactly a month from now. There is no way of determining whether rain will occur at that time. The precipitation parameter can be regarded as uncertain but as varying within a certain interval and as showing a particular distribution. Both this interval and this distribution can be studied on the basis of historical data and expert judgement.

In the standard method, the uncertainties involved are taken into account in the method itself, even if this is not always obvious. There is a certain degree of safety built in. The use of simple computational approaches can be more problematical, one's easily being forced to select a so-called design value for each of the uncertain variables. The fire load density or the fire growth rate are examples of variables that can be difficult to determine, raising a variety of questions, such as

- What sort of fire should serve as the design?
- What course of development of a fire would be most likely?
- What is the worst fire that can be expected?

Although no clear answer can be given to such questions, efforts to provide answers of some kind are underway, partly within the framework of the international standard of fire safety engineering (ISO 1997). Although uncertainty regarding many such variables is considerable, certain intervals within which values can be expected to lie can be estimated. If a design fire needs to be selected for use in simple computations, it can be sensible to choose a reasonable design fire on the conservative side. Always selecting a value implying the worst possible consequences would yield an exaggerated picture of the risks involved. To examine the importance of a particular variable for the final result, a sensitivity analysis is sometimes carried out, such that the effect of doubling the size of the variable, for example, may be examined so as to decide whether the values selected are conservative enough.

The following matters need to be investigated:

- variations in the input data
- the effects of simplifying problems
- the effects of various aspects of the scenario, e.g. of doors being open
- the reliability of the technical system

Those variables found in the sensitivity analysis to be particularly important should perhaps be selected in a more conservative manner than those that have a lesser effect on the results. A sensitivity analysis should indicate which variables are important and what should be done to reduce uncertainty concerning them. How a sensitivity analysis is carried out is described in the Australian handbook entitled Fire Engineering Guidelines (1996).

4. DESCRIPTION OF THE BUILDING AND DESIGN ALTERNATIVES

4.1 ARCHITECTURAL DESIGN

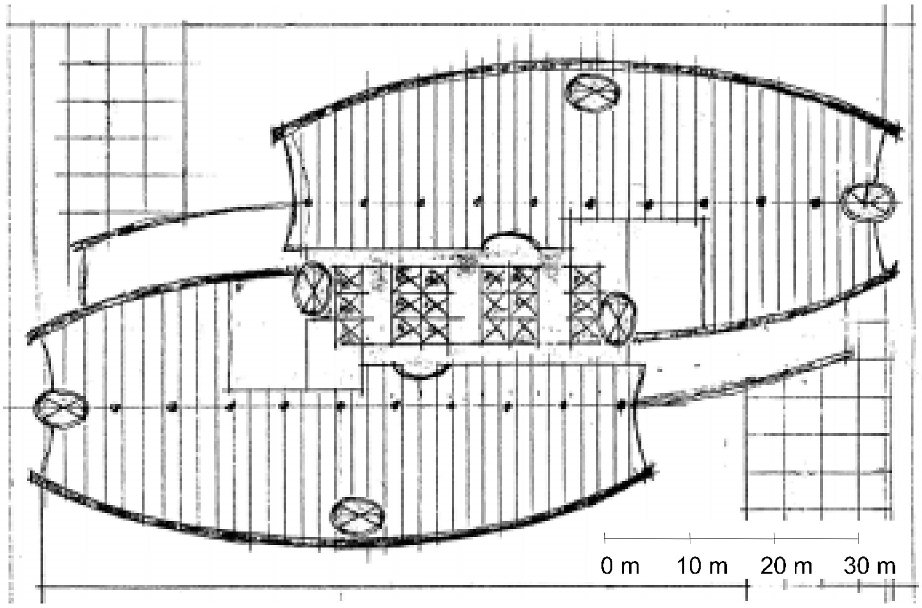


Figure 4. Floor plan layout of the building.

The building in question is a double elliptically formed 20-storey office building with a basement. The basement includes various services rooms for the building as well as parking spaces. The ventilation equipment is located in the attic.

Floors 1 and 2 are assembly rooms including a foyer, a cafeteria, an insurance company, office services, building maintenance, etc. The first two floors are rectangular in shape. On the ground floor there are two arcade entrances.

Floors 3-20 contain office premises with modular office rooms. It is intended that these floors be able to provide flexible tenant accommodation, with 1-2 companies per floor.

All workplaces have direct or indirect sunlight, which is required by regulations. The top floor has a restaurant and can also be used for conferences.

A maximum of six staircases passes through each floor of the building. The number of staircases depends on what design alternative is used.

In the middle of the building there is a protected lobby with four sets of elevators, a total of 18 altogether. Storage, restrooms and kitchens are located in the vicinity of the elevators.

Each floor has an area of 2000 m^2 that can be used as office area (gross area is 3000 m^2), and is intended to accommodate up to 200 persons on each floor. The top floor is designed to accommodate a maximum of 800 persons.

4.2 DESIGN ACCORDING TO THE STANDARD METHOD

The required fire protection is reported below, designed in accordance with standards and recommendations in building guidelines and handbooks, without using fire safety engineering calculations. This method meets the building function requirements on the basis of previous experience and practice in Sweden. For further information on the building code requirements, see appendix 1.

Depending on their function, elements of structure are assigned to classes R (load bearing), E (integrity) and I (insulation). The classification for doors could be combined with the designation C (for doors with an automatic closing device). The symbols are those used in the Swedish building code (BBR 94). The fire resistance classes used in accordance with the code are based on fire load densities lower than 200 MJ/m^2 (surrounding area). The classes could be applied, without special examination of the actual fire load, for dwellings, offices, schools, hotels, garages for cars, store rooms for residents, and comparable fire compartments.

4.2.1 Fire resistance classification

The office building is classified Br1. An office building is assessed as contain a fire loading of less than 200 MJ/m^2, and should therefore be fire resistant for at least 90 minutes (R90) in the case of structural and 60 minutes (EI60) in the case of partitioning construction. Structural elements and fire compartment separation partitions and floor structures are permitted to contain combustible material, for example wood.

The fire compartment separation partitions are to consist of steel studs and 2 x 13 mm gypsum plaster sheets on each side (EI 60). The indoor windows and doors in the fire compartment walls are to be made of class EI 60 (60 minutes).

The surface layer must be of the highest class (Class I), in this case at least 9 mm gypsum plaster sheets. The same requirements apply to walls in staircases and assembly rooms for more than 150 persons. Other walls can be made of class II, which permits wallpaper but not unprotected wood as the surface layer material.

Facades and roofs are to be made of non-combustible material, except for the facade surface of the ground floor, which can be combustible. The roof surface can be combustible, but should contain material that is difficult to ignite, on top of non-combustible material.

The components of the HVAC-systems should in principle be made of non-combustible material and should not contribute to the spread of fire.

4.2.2 Escape routes

Escape routes are defined as either doors to the open air or other fire compartments in the building (staircases and corridors) or other office fire compartments, which lead to the open air. Occupants are assumed to evacuate without the help of the Rescue Services. The maximum permitted walking distance to the nearest escape route is 45 metres for offices, where the coincident distance to another escape route is to be multiplied by 1.5. Six staircases are included, due to the requirements concerning maximum allowable travel distances. The two centre staircases are designed to be staircases Tr1 and the other four to be staircase Tr2. One staircase, Tr1 is in communication with other spaces through a protected lobby, which is open to the external open air (other solutions also exists). The doors to the lobby and the staircase are both EI-C30. If the lobby is furnished one of the doors should be EI-C60. A staircase Tr2 is in communication with other spaces through a fire compartment. The door to the staircase, Tr2 is of class EI-C60.

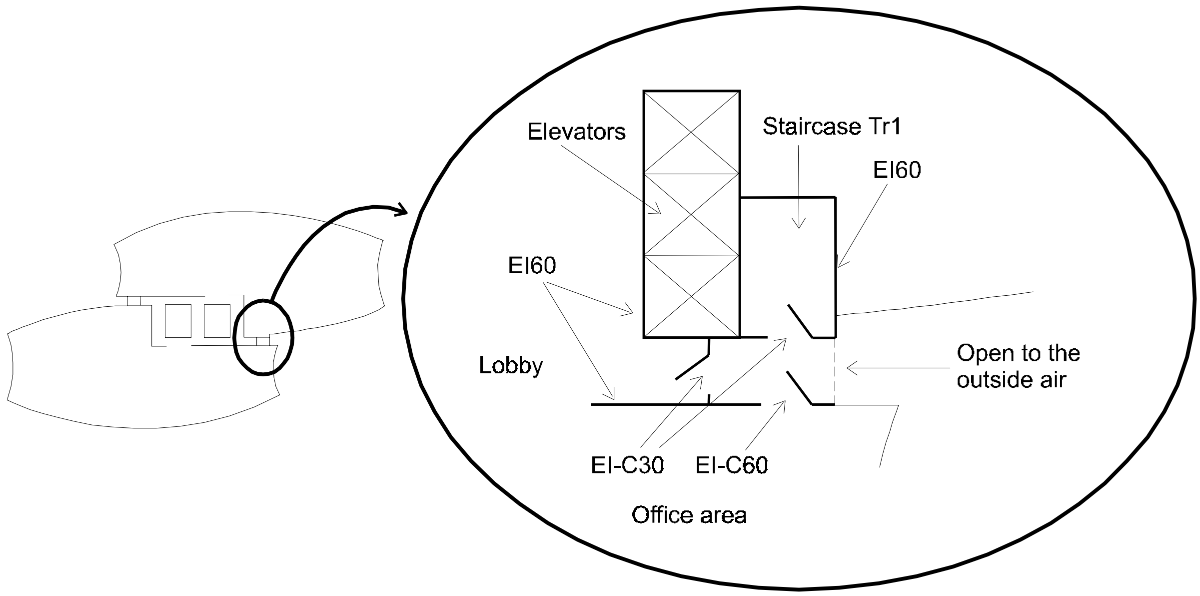


Figure 5. Drawing of staircase Tr1 applicable for exits 3 and 4 (see figure 6). The figure shows the staircase in communication with other spaces through a protected lobby. Note the extra door to the office area.

The escape width required is generally 0.9 m for door openings). In premises designed for more than 150 persons, it is recommended that the width be 1.2 m. The total width of emergency exits should be equal to 1.0 m per 150 persons. The building owner has chosen all staircases to be 1.2 m and the effective door width to be 1.0 m, which fulfils the requirements above.

The equipment required for escape routes are exit signs, and emergency lighting in meeting rooms, basement corridors and staircases.

4.2.3 Fire compartment subdivision

Each staircase is a separate fire compartment. Each group of elevators is likewise a separate fire compartment. The areas for kitchens, restrooms, etc. are also separate fire compartments. Each floor is separated into two fire compartments. The floors, in turn are separated from each other.

Unless there is a sprinkler system, no fire compartment, apart from the staircases, is allowed to comprise more than two floor levels. In this building each floor is separated from each other, and changes of these will not lead to any savings because of all other requirements in the building code.

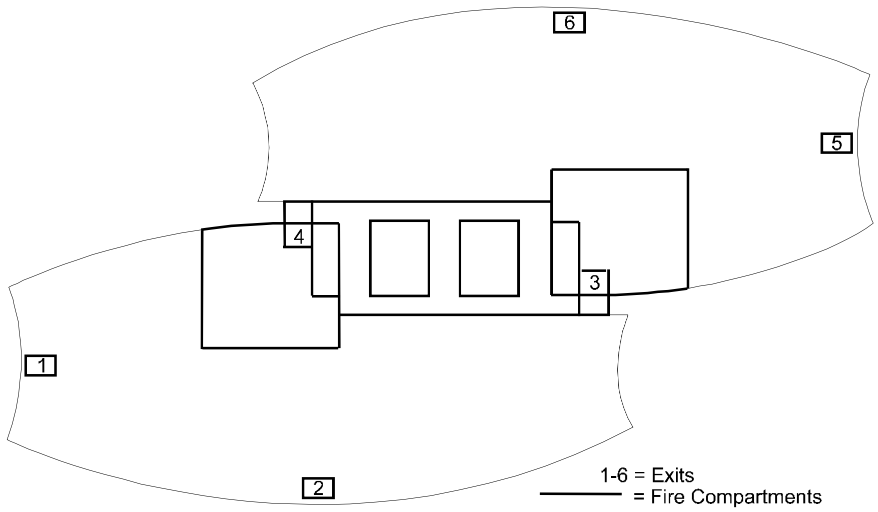


Figure 6. Fire compartment subdivision of office floor

4.2.4 Installations

The four staircases (Tr2) have smoke ventilation to facilitate extinguishing of fire as well as rescue activities. Hatches or fans at the top of staircases are opened/started manually from the entrance.

The fire compartments in the basement are smoke and heat ventilated through vents to ground level, which is opened manually. The area of the hatches shall correspond to at least 0.5% of the floor area of the fire compartment. The smoke and heat ventilation in the basement shall be designed to facilitate extinguishing.

All premises have access to fire extinguishing equipment in the form of hand-held fire extinguishers, or internal fire hydrants. The extinguishing equipment is supposed to be used by persons in the building in case of fire. All staircases are equipped with rising mains for the fire department.

In order to fulfil the general clause concerning escape in the event of fire a manual evacuation alarm is installed on each floor. When someone has pushed the alarm button, the evacuation alarm starts, on that floor and on the two floors above and below, a signal also going to the lobby personnel. If no personnel are available the alarm goes to the Rescue Service.

Signs used to indicate an escape route or to inform about where the nearest escape route is located are present in the whole building. They are in compliance with the European Unions-regulation on safety at work. In the basement, the signs are also equipped with emergency lighting. In other parts of the building the signs are backlit or illuminated by the normal lighting depending on the situation. All staircases have emergency lights for at least 60 minutes.

4.2.5 HVAC-systems
An air supply and exhaust system with fans is installed on the 10th floor and in the attic. Open shafts and ducts go through the floors. The shafts are made with 60 minutes fire resistance, by means of walls made of 3x13 mm gypsum plaster sheets. The fan room in the attic common to almost the entire building, is a separate fire compartment and has 60 minutes fire resistance and the ventilation channels 15 minutes in general. The fans are shut off at night and when the fire alarm goes off.

In addition to the above measures, the ventilation ducts are insulated along lengths of about 1-2 m on each side of a fire compartment wall. Alternatively, a fire damper is installed in the ducts where they pass the fire compartment boundaries, which is used in this design.

Several alternatives are generally approved for protection against smoke spread. The safest and most expensive method is to have separate systems for every fire compartment. It is also possible to use smoke dampers in ducts between different fire compartments, which is used in this design.

4.3 DESIGN ACCORDING TO THE ALTERNATIVE STANDARD METHOD
In the old prescriptive building code (NR) it was recommended that the travel distance could be increased if a sprinkler system was installed. This is one of the options in the alternative method. A sprinkler system is therefore installed as a solution of the form described in the alternative method. This allows the required travelling distance to an escape route to be increased by 33%. It allows the external staircases on the long side of the building to be omitted.

4.4 DESIGN ACCORDING TO THE FIRE SAFETY ENGINEERING METHOD
In this solution engineering equations are used to justify the tradeoffs. Choice of tradeoffs depends on the competence and knowledge of the consultant, since it is too easy to prove anything by just using a deterministic engineering design. Normally tradeoffs are chosen to permit longer travel distances. These are installing a detection system, alarm system, smoke exhaust system or a sprinkler system. In this report three different solutions have been examined with various combinations of sprinkler system, detection system and different number of exits. The following combinations have been studied:

- **Fire safety engineering method a**, with smoke detectors and alarm bell, no sprinkler system and exit 1,3,4 and 5 available
- **Fire safety engineering method b**, with a sprinkler system, alarm bell, no smoke detectors and only exit 3 and 4 available
- **Fire safety engineering method c**, with smoke detectors, alarm bell, no sprinkler system and only exit 3 and 4 available

The calculations using the design equation are presented in chapter 5.

In the case when only the two center staircases are used there is a risk that both of them can be blocked at the same time. This could be from a fire in the lobby, or from smoke spread trough the elevator shafts. The allowable amount of combustibles in the lobby has to be limited and the elevator doors must be smoke tight. In addition to this an extra door direct from the office floor to the protected lobby at the staircase Tr1 is installed. This door can be used if for some reason the whole lobby area is blocked or if the fire occurs so that it blocks the entrance to the lobby area. The protected lobby outside the staircase Tr1 is in connection to the external open air.

5. ENGINEERING CALCULATIONS

5.1 DESIGN FIRE SCENARIOS

The design fire used is a ”medium” t-squared fire according to the BSI guide (1997). The heat release rate per unit area is 250 kW/m^2, the maximum rate of heat release being assumed to be 4 MW. It is possible for the fire to continue to grow, since more fuel is available, but this is not likely to occur during the time period of interest. The fire is not affected by the ventilation system since it is shut off in case of fire. The arrival of the fire brigade does not affect the fire scenario in the time frame studied. The BSI guide does not recommend any particular smoke spread model, which indicates that the designer has to deal with the uncertainty contained in the model employed. In this case CFAST 2.01 (appendix 4) is used (Peacock et al, 1994). Magnusson et. al. (1995) suggest that the time up to the critical conditions can be extended by 35% when smoke layer height is used as the basis for measurement. A model correction factor has been used in accordance with the reference. The sprinkler activation times and smoke detector activation times are calculated using the computer model Detact-t^2 (Evans et al 1985) and are presented in the table 1. On the basis of an extensive sensitivity analysis, see appendix 5, the time to critical conditions was chosen as being 660 s.

The critical levels for untenable conditions were chosen according to the recommendations in the Swedish building regulations as being 1.9 m (room height 3m), which is a rather conservative value. In analysing the results, the choice of critical conditions that prevent people from continuing to evacuate a room was based on values recommended in the building code BBR 94. When the critical conditions develop, this does not mean that a person exposed to them will necessarily die or be seriously injured. Rather, it means simply that remaining there under such conditions is undesirable and that society (represented by building laws) does not accept persons to be there. Whenever conditions reach this critical level or when smoke starts to exit through an opening, the escape route is considered to be blocked or unable to be used. The time elapsing until the critical conditions come about varies with such factors as where a person is located in the building, how far the person is from the fire, the size and shape of the rooms, and the connections found between different rooms.

To be able to compare the risk involved in the different design solutions a number of scenarios have been studied. In the different scenarios the design equation in chapter 3.3.1 has been used to calculate the evacuation margin. Since the risk comparison is relative it is assumed that the probability of a fire starting is equal to one. The data used in the calculations comes mainly from handbooks. It can then be argued that no extensive sensitivity analysis is presented in this report. This is a necessity when the result from the design equation is going to be the basis for decision. In this report using the risk based verification method primarily does the sensitivity analysis. The use of handbook values in calculating the consequences in the sub scenarios and only using the results for relative comparison does not require any extensive uncertainty analysis.

The following design solutions have been studied:

- **Standard method**, with manual detection and alarm bell
- **Alternative standard method**, with a sprinkler system and alarm bell
- **Fire safety engineering method a**, with smoke detectors and alarm bell, no sprinkler system and exit 1, 3, 4 and 5 available
- **Fire safety engineering method b**, with a sprinkler system, alarm bell, no smoke detectors and only exit 3 and 4 available
- **Fire safety engineering method c**, with smoke detectors, alarm bell, no sprinkler system and only exit 3 and 4 available

For the restaurant on the top floor a special study has been made. The solution according to fire safety engineering method b was improved for the restaurant floor. The alarm bell is replaced with a voice message system and a smoke detection system.

5.2 EVACUATION TIME

5.2.1 Detection and reaction times

Scientific knowledge at the moment is not sufficient to model the behaviour of the different persons in the building with any precision. Rather, a rough assessment of the course of events over time needs to be made.

	Time	Reference
Sprinkler activation time	230 s	calculated (appendix 4, 5)
Smoke detector activation time	185 s	calculated (appendix 4, 5)
Manual activation time	300 s	assumed
Reaction time, no alarm	300 s	assumed
Reaction time, alarm bell	240 s	BSI guide (1997)
Reaction time, voice message	180 s	BSI guide (1997)

Table 1. Detection (activation) and reaction times used in the analysis.

5.2.2 Travel time

The travel time calculations were performed using the computer program SIMULEX 2.0 (Thompson et al, 1995) and simple handcalculation methods. The hand-calculation methods use a flow of 1.2 person/s in the stairs and a flow of 1.2 person/s through a door (effective width 1.0 m). The walking speed taken is 1.3 m/s for the office people (Jönsson et al 1994). The critical factor in the hand calculation is the flow through the door opening.

Three different general scenarios were studied. In each scenario its design value is given as if that scenario was the only one. The results from these scenarios must be compared. In the study it was found that phased evacuation was the most critical, and the travel times from that is used in the design equation. The purpose of the calculations is to find design values to be used in the design equation described in chapter 3.3.

1. Simultaneous evacuation of an office floor
In the evacuation of a floor the simulated scenarios assume that a fire starts in one part of the floor and that the whole floor is evacuated. In the scenarios, different doors are blocked in the part of the floor where the fire starts. All scenarios are shown in appendix 6.

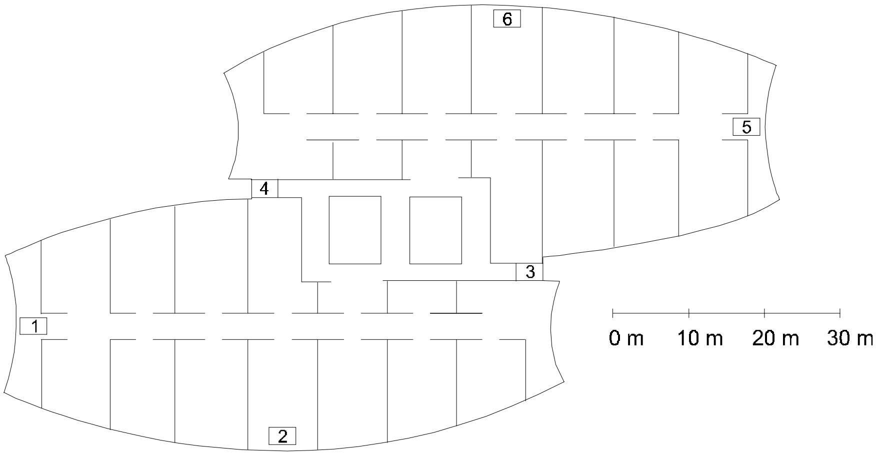


Figure 7. Exit numbers and room configuration for modelling the travel time.

	Available staircases (exits)						Travel time
	1	2	3	4	5	6	
Standard method	x	x	x	x	x	x	70 s
Alt. standard method	x		x	x	x		80
Fire safety engineering method a	x		x	x	x		80
Fire safety engineering method b			x	x			100
Fire safety engineering method c			x	x			100

Table 2. Number of staircases and anticipated travel time for each scenario. For more information of the scenarios see table 4.

2. Phased evacuation of five office floors
The evacuation procedure (see chapter 4.2.4) states that in case of an alarm five floors will be evacuated; the fire floor, the two floors above and two floors below it. It must therefore be determined whether or not it is possible to evacuate five floors without having unreasonably large travel times.

The critical part in these calculations is obviously the capacity of the staircases and the occurrence of queuing in front of them. The scenarios are chosen as above. The fire floor and two floors above and below it are evacuated. Since the restaurant is on the top floor it has not been taken into account in the study of phased evacuation. The two centre staircases are the most important, because people tend to go to the exit where they entered the floor. The number of people entering the centre staircases from each floor are found in appendix 6 and shown in table 3.

In the modelling using SIMULEX consideration was taken to the travel time in the staircases and also the queuing in front of them. Because of symmetry only one of the two centre staircases needed to be dealt with in the computer program. The travel times are shown in parentheses in table 3 and represent the travel time to evacuate the fire floor.

It is unreasonable to think that the people of the non-fire floor will have the same reaction time as on the fire floor. A difference in the reaction time of 120 s is therefore introduced as natural difference or is accomplished by delaying the alarm to the non-fire floors. The obtained travel times are shown in table 3. If these values are compared to those of a single floor it is obvious that phased evacuation would be the critical and used as design value in the engineering calculations.

	Number of persons from each floor in each staircase	Travel time
Standard method	80 persons	(180 s) 120 s
Alternative standard method	90 persons	(220 s) 125 s
Fire safety engineering methods b and c	100 persons	(250 s) 135 s

Table 3. Simulation results for phased evacuation. Values in parenthesis are without difference in reaction time.

3. Simultaneous evacuation of the restaurant floor

In the study of the restaurant floor it was assumed that there were 400 persons in each part of the floor. Further it was assumed that most of the people would leave the same way they entered. This means that evacuation through staircases 3 and 4 would be the most critical. In the computer simulations the office floor configuration according to figure 7 was assumed to simulate in a simplified way the influence of different floor layouts. No sensitivity analysis was made, since the purpose was only to demonstrate the differences between this floor and the other office floors. The evacuation strategy is different from the rest of the building, since it is assumed that the evacuation of the restaurant floor will first occur before evacuation of the other floors. This might require that the compartmentation to the restaurant floor have to be increased. From the simulation a design value of 255s were chosen.

5.3 VERIFICATION OF DESIGN ALTERNATIVES

The following scenarios were studied using the risk based verification method and the fire safety engineering method principles.

	t_c -	t_d -	t_r -	t_t =	M
Standard method, Manual detection and alarm bell	660	300	240	120	0
Alternative standard method, Sprinkler system and alarm bell	N.A.	230	240	125	not critical
Fire safety engineering method a, Smoke detectors and alarm bell, no sprinkler system	660	185	240	125	110
Fire safety engineering method b, Sprinkler system, alarm bell, no smoke detectors and only exit 3 and 4 available	N.A.	230	240	135	not critical
Fire safety engineering method c, Smoke detectors, alarm bell, no sprinkler system and only exit 3 and 4 available	660	185	240	135	100
Restaurant floor Sprinkler system, smoke detector, voice message and only exit 3 and 4 available	N.A.	185	180	255	not critical

Table 4. Summary of escape margin for the design scenarios in the different alternatives.

To an untrained eye, it looks as though all the alternatives would be appropriate, and they also are according to the fire safety engineering method, if used in a simplified way. The longer evacuation times for phased evacuation could also be used if the alarm bell was changed to use of a recorded message. Viewed in the same way, a sensitivity analysis would indicate acceptance. Take case c; change it to use of a recorded message and a “fast” fire growth rate. The result then would be: 465-185-180-135 = -35s. Not too bad, it would appear (not taking account of the faster response of the smoke detector). This corresponds to consequence of 42 persons exposed to critical conditions. If consideration is taken to faster response of the smoke detector the result would be: 465-113-180-135 = 37s.

5.4 RELIABILITY OF TECHNICAL SYSTEMS

The possibilities for assessing the reliability of a technical system today are rather poor. In most fire safety planning it is simply assumed that a system will function 100 %. Such is not the case in reality. The reliability is dependent, of course, on how appropriately the program of controls is carried out. For further discussion see appendix 7.

In some alternatives the fire alarm can be started either manually by pressing a button or automatically by means of a signal from the sprinkler or from the smoke detectors. It is assumed that, if the sprinkler or the smoke detector functions properly, the fire alarm will be set off automatically with the degree of reliability listed in the table. If neither the sprinkler nor the smoke detector sets off the alarm, it must be started manually. The reliability of manual activation of the fire alarm’s succeeding, listed in the table as 0.50, represents the probability that someone will push the alarm button. This necessitates some person’s going to the spot where the manually operated fire alarm is situated so as to activate it. Since the latter step is one that is only seldom carried out, a low probability of occurrence is attached to this function. Operator mistakes are a common cause of errors here, technical errors being another cause.

	Probability of failure	Reference
Automatic sprinkler system	0.05	BSI guide (1997)
Smoke detection system	0.10	BSI guide (1997)
Alarm bell	0.15	BSI guide (1997)
Manual detection	0.50	Estimate

Table 5. Probability of failure used in the event trees.

5.5 RISK COMPARISON

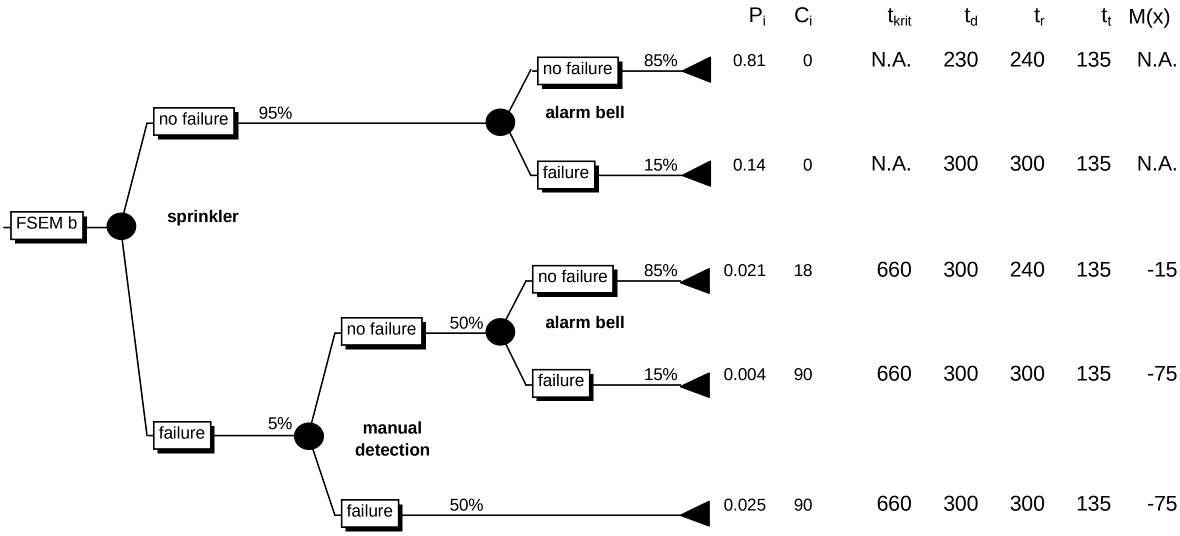


Figure 8. Event tree evaluation of the design alternative FSEM b.

In figure 8 the event-tree from the fire safety engineering design b is shown as an example. It should be noted that the calculations are done given that a fire occurs. This design has a sprinkler system, no smoke detectors and only two escape routes (stairs 3 and 4). The different times in the equation for the evacuation margin M are given. The event-trees from the other design alternatives are shown in appendix 8. The consequence is calculated in a simplified way from the phased evacuation calculations.

One simple way to compare the different designs would be to compare the average risks, calculated by $\Sigma(P_i \times C_i)$.

Design according to	Average risk
Standard method	41
Alt standard method	3
Fire safety engineering method a	15
Fire safety engineering method b	3
Fire safety engineering method c	18
Restaurant floor	3

Table 6. Average risk for the different alternatives.

As discussed in chapter 3.4.1, the average risk has its disadvantages as a basis for the decision of whether a design should be accepted. Instead, use should be made of the information in an event tree, as displayed in a risk profile. The risk profiles corresponding to the event-trees are shown in figure 9.

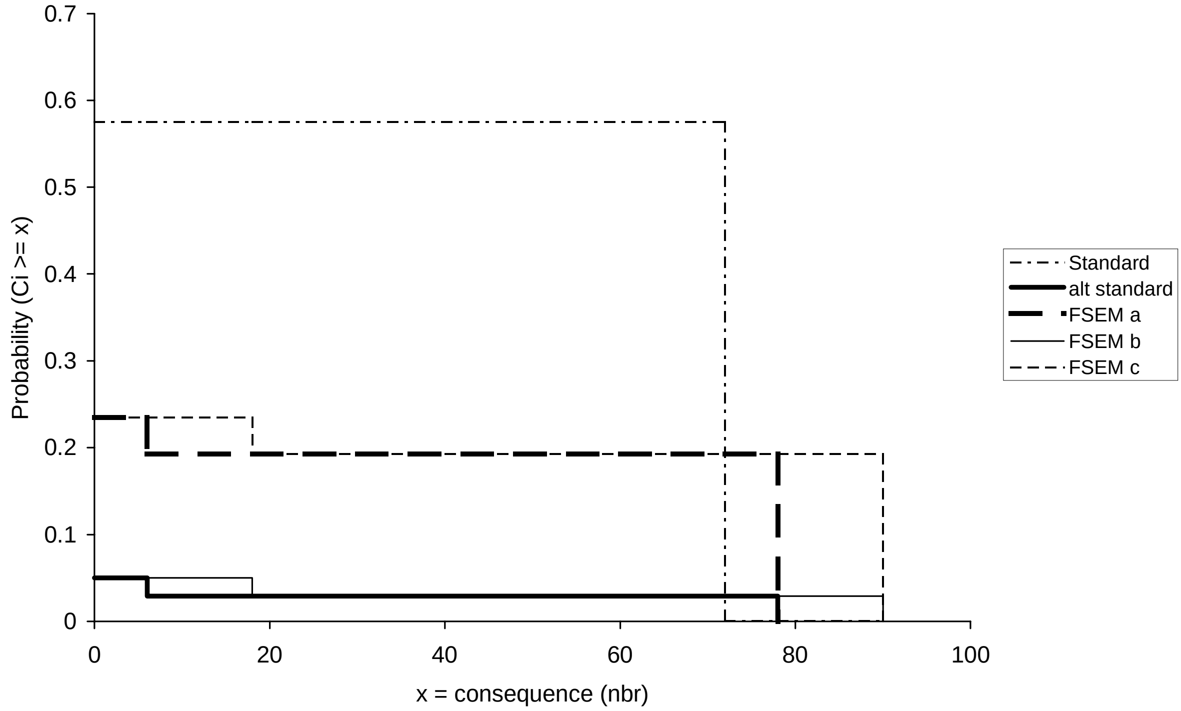


Figure 9. Risk profiles for the different design alternatives evaluated

In the restaurant floor the design solution (Fire Safety Engineering method b) was already improved by installing a smoke detector system and a voice message system. The event tree is shown in appendix 8. It gives an average risk of 2.5, which is acceptable low. Its risk profile starts at a very low probability, but has a very high consequence of 400 persons. One design improvement, besides the ones described above, could be that extra staircases are installed to enable people to evacuate to the floor underneath. In this case the fire compartmentation requirements between the floors has to be increased.

6. RELATIVE FINANCIAL COMPARISON

No full financial or fire engineering analysis, which compares the different design alternatives has been done, but merely a rough estimate of the construction costs for the different alternatives. In the calculations the savings that could be made by designing the insulation of the load bearing steel structure for a natural fire instead for the standard ISO834 fire is not included, nor are savings that could be done the same way for partitions. This is not done because the calculations in chapter 7 only exemplify the procedure. In the prescriptive building code this procedure was accepted and was considered an early attempt to introduce performance-based codes.

The calculations are very rough estimates and some of these prices have been compared to other prices available. Differences of 100% were obtained.

6.1 GENERAL ASSUMPTIONS

All prises consider planning, construction costs as well as overheads in price valid in January 1998.

1 dollar = 8 SEK (Swedish krona)

6.2 SPECIFIC COSTS

a) A fully equipped staircase Tr1 costs 3.6 MSEK
b) A fully equipped staircase Tr2 costs 3.6 MSEK
c) Signs, emergency lights, alarm bells etc in escape routes costs 25 kSEK/floor
d) Sprinkler system, excluding water tanks costs 960 kSEK/floor
e) Smoke detection system according to Swedish standard RUS 120:4 (1987) costs 285 kSEK/floor
f) Additional cost for voice message system 15 kSEK/floor

6.3 DESIGN SOLUTION COSTS

In these calculation the restaurant floor is considered to be the same as the office floors

Design according to:	**Includes:**	**Cost:**
Standard method:	$2\times a + 4\times b + 20\times c =$	22 MSEK
Alternative Standard method:	$2\times a + 2\times b + 20\times c + 20\times d =$	34 MSEK
Fire safety engineering method a:	$2\times a + 2\times b + 20\times c + 20\times e =$	21 MSEK
Fire safety engineering method b:	$2\times a + 20\times c + 20\times d =$	27 MSEK
Fire safety engineering method c:	$2\times a + 20\times c + 20\times e =$	13 MSEK

Table 7. Relative design costs of different solutions.

7. DESIGN OF THE LOAD BEARING STRUCTURE

7.1 INTRODUCTION

A structural engineer has designed the building in a simplified manner. The structural system will not be described in detail. This chapter will only show some examples of what you can do as a fire protection engineer, and does not describe all calculations and engineering judgements needed in the design process. In the calculations a fictive room size (9.5 m x 10.5 m) has been chosen just for demonstration purpose. This could represent a conference room.

In all the calculations the design manual ”Fire Engineering Design of Steel Structures” (Pettersson et al 1976) has been used. A sample calculation is shown in chapter 7.4. In the case where sprinklers are installed the recommendations in Eurocode (1994) were used. There it is recommended that the fire load density is reduced to 60%. A better approach, depending of the design of the sprinkler system, is to use a temperature - time curve for a fire taking into account the effect of the sprinkler, but then how is the reliability of the sprinkler system taken into account? This is done in the Eurocode by the reduction of the fire load and not relaying on that the sprinkler system will extinguish the fire.

7.2 BUILDING CODE REQUIREMENTS

”Load bearing structures shall be designed and sized so that in the event of fire there is adequate structural safety with respect to material failure and instability in the form of local, overall and lateral torsional buckling and similar. Parts of the load bearing structure including supports, joints, connections and similar, shall be designed so that collapse does not occur, during a specified period of time. This time period shall be in accordance with the fire resistance classes for elements of structures set out in subsection 5:82, under fire exposure conditions in accordance with the Swedish Standard SIS 024820 (ISO 834)”, see appendix 1.

”As an alternative, design of the load bearing structure may also be based on a model of a natural fire sequence in accordance with subsection 5:83”, see appendix 1 and further reference to appendix 1 (BKR94, 1994).

The requirement for the load bearing structure is 90 minutes, as seen in table a in appendix 1, chapter 5:8 from the building code, and 60 minutes for the partitions, chapter 5:6.

7.3 LOAD BEARING STRUCTURE AND PARTITIONS

The structural elements are made of steel. The internal walls are made of steel studs, insulated on each side with two 13 mm gypsum plaster sheets.

The following fires have been studied regarded the required insulation thickness:

- **(S)** Standard fire temperature curve according to ISO 834, 90 minutes.
- **(N)** Natural fire, as described in reference in Pettersson et al (1976), with a fire load density of 644 MJ/m^2 total floor area**.** In the case of sprinklers 60% of the fire load density was used.

For the above combinations one beam centrally located and one column inside have been used for the calculations. The results are presented in table 7.1.

	(S)	(N) without sprinkler	(N) with sprinkler
Beam	23 mm	9 mm	5 mm
Column	21 mm	7 mm	4 mm

Table 8. Minimum required insulation thickness in mm.

7.4 SAMPLE CALCULATION

The sample calculation is done for a three sided fire exposed beam. The fire exposure is a natural fire and a sprinkler system is installed. The nomenclature is according to the design manual written by Pettersson et al (1976).

q = 60 kN/m, distributed load

$W = 3550 \cdot 10^{-6}\ m^3$

L = 8,7 m simply supported

A_i = 814 mm

HE 500 A profile.

$V_s = 9708\ mm^2$.

$\sigma_s = 270$ MPa

$$h = \frac{1{,}8 \cdot 7{,}5 \cdot 1{,}8 + 2 \cdot 0{,}9 \cdot 2{,}0 \cdot 2{,}0 + 1{,}6 \cdot 2{,}0 \cdot 2{,}0}{(1{,}8 \cdot 7{,}5 + 2 \cdot 0{,}9 \cdot 2{,}0 + 1{,}6 \cdot 2{,}0)} = 1{,}87\ \text{m}$$

$$\frac{A \cdot \sqrt{h}}{A_{tot}} = \frac{(1{,}8 \cdot 7{,}5 + 2 \cdot 0{,}9 \cdot 2{,}0 + 1{,}6 \cdot 2{,}0) \cdot \sqrt{1{,}87}}{2 \cdot (9{,}5 \cdot 10{,}5 + 9{,}5 \cdot 3{,}2 + 10{,}5 \cdot 3{,}2)} = 0{,}085\ \text{m}^{1/2}$$

$$f = \frac{644 \cdot 10{,}5 \cdot 9{,}5}{2 \cdot (9{,}5 \cdot 10{,}5 + 9{,}5 \cdot 3{,}2 + 10{,}5 \cdot 3{,}2)} = 196{,}2\ \text{MJ/m}^2$$

50% concrete and 50% gypsum in the surrounding surfaces $\Rightarrow$

$$k_f = \frac{0,5}{0,8} \cdot k_G + (0,5 - \frac{0,5}{0,8} \cdot 0,2) \cdot k_B \Rightarrow$$

$$k_f = \frac{0,5}{0,8} \cdot 1,22 + (0,5 - \frac{0,5}{0,8} \cdot 0,2) \cdot 0,85 = 1,08$$

$\left(\frac{A\sqrt{h}}{A_{tot}}\right)_{fict} = 1,08 \cdot 0,085 = 0,092\ m^{1/2}$, fictitious opening factor

f_{fikt} = 1,08 · 196,2 = 212 MJ/m^2, fictitious fire load / total area of the enclosure

$$\text{case 2} \Rightarrow 60 \cdot 10^3 = (\beta + \Delta\beta) \cdot \frac{8 \cdot 270 \cdot 10^6 \cdot 3550 \cdot 10^{-6}}{8,7^2}$$

$$\Rightarrow \beta + \Delta\beta = 0,59$$

$$\Rightarrow T_s = 515°C$$

$$\left.\begin{array}{l} \left(\frac{A\sqrt{h}}{A_{tot}}\right)_{fict} = 0,08\ m^{1/2} \Rightarrow \frac{A_i}{V_s} \cdot \frac{\lambda_i}{d_i} = 1750 \\ \left(\frac{A\sqrt{h}}{A_{tot}}\right)_{fict} = 0,12\ m^{1/2} \Rightarrow \frac{A_i}{V_s} \cdot \frac{\lambda_i}{d_i} = 2459 \end{array}\right\} \Rightarrow$$

$$\left(\frac{A\sqrt{h}}{A_{tot}}\right)_{fict} = 0,092 \Rightarrow \frac{A_i}{V_s} \cdot \frac{\lambda_i}{d_i} = 1963$$

$$T_s = 515°C \Rightarrow \lambda_i = 0,201\ W/m°C$$

$\Rightarrow d_i = \frac{0,201}{1963} \cdot \frac{0,814}{9708 \cdot 10^{-6}} = \underline{\underline{9\ mm}}$ (Gypsum)

8. DISCUSSION AND CONCLUSIONS

The current Swedish performance based building code does not provide any criteria that could be directly translated into a risk measure, not yet at least. Due to this lack of information, a design according to the earlier prescriptive code, i.e. the standard method, is used as a comparative design criterion and the risk comparisons are made given that a fire occurs. In this case study, the alternative standard method seems to be most appropriate, because that design would have been the most probable according to the state of the art of designers. It is also questionable how applicable the standard method is for this type of building.

The design chosen to represent the current risk level in this type of building is not to be seen as absolute. It merely gives an indication of a level of risk that is accepted by society. Other accepted solutions can result in somewhat different risk profiles, but still be valid. Recent studies have shown that the risk level in buildings erected in accordance with the standard method (NR 1988) varies.

If a design is to be compared with the design acceptable in terms of the earlier prescriptive building code, its risk profile should be close to the curve for the alternative methods design curve or lie under that curve in figure 9. This guarantees that even if the design has the same average risk, it also has the same balance between accidents with small and large consequence.

In the prevailing engineering design method used (described in chapter 3.3) a single state equation together with conservative deterministic values are used. The application of this method has proven not to give satisfactory results, especially when the reliability and use of technical systems are introduced. This method alone is not intended to be used on a system level. From the study (Boverket 1997) it was concluded that an important step is to continue to develop methods based to avoid the misuse of engineering methods.

The fire safety engineering designs have marginally greater consequences than the standard and alternative standard method. The alternative FSEM b has the risk profile closest to the “acceptable” curve and has a low average risk value as well (figure 9). The solution with only two centre staircases, protected lobbies open to the outside and a sprinkler system is thus recommended. The solution could be improved so that the F N-curve moves more to the lower left corner by installing a smoke detector system. Additional improvements could be: installing voice message system instead of the alarm bell, smoke extract systems in the lobby as backup if sprinkler fails and “fire” elevators.

By comparing the risk profiles it might look odd that the number of staircases does not affect the safety very much. The reason is that most of the people tend to leave the same way they entered. The positions of the staircases in this building are such that they do not contribute very much to the safety. Of course they represent extra safety and access routes for the rescue service. In this report no consideration is taken to the rescue service and their ability. In Sweden their exists no good engineering design guidelines to assure safe access in high rise buildings for the rescue service.

The calculations of the load bearing structure show that you certainly can save some insulation materials when using the real temperature - time process in the fire compartment as your design fire (natural fire sequence), instead of the standard ISO 834 fire curve. In the examples gypsum plaster sheets have been chosen as insulation material, and as shown the savings are not that great because the gypsum board only comes in certain sizes (9 and 13 mm). If some other insulation material had been used, the savings would have been greater. Another fact added to this is that the steel columns have not been used to their full extent because of the simplified design.

It is clear that the only two acceptable solutions are the alternative standard method design and the design with fire safety engineering method (FSEM b), which has two staircases Tr1 and a sprinkler system. The prices for the fire protection systems according to the calculations in chapter 6 are 34.1 MSEK (4.3 Million dollars) and 26.9 MSEK (3.4 Million dollars) respectively. The possible savings correspond to 11000 consulting hours for a Swedish fire safety consultant. If the fire safety engineering solution were to be improved as suggested by installing a smoke detection system, the cost for that design would then be 32.6 MSEK (4.1 Million dollars).

The other two fire safety engineering solutions are less expensive 20.6 MSEK and 13.4 MSEK respectively, but they have not acceptable fire safety if the alternative standard method is used as acceptable level. However, as demonstrated in chapter 5.3 the deterministic engineering calculations in the fire safety engineering method case c could perhaps persuade someone with low fire safety engineering knowledge to accept that solution. This would give a low construction cost but not accepted safety in the building according to the comparisons made by the risk based verification method.

The examples in this report demonstrate the benefits of having a performance-based building code. The design can be done more cost effective using fire safety engineering method and still having the same safety in case of fire in the building. This would not have been possible with a prescriptive regulation. It is also obvious that a risk based verification method is needed as a complement to deterministic fire safety engineering method.

No final judgement is made of which solution to choose for the final design. The engineering approach used in this report is very elaborate and not straightforward, since the report is made for this conference and the design solutions from the fire safety engineering method only concentrate of achieving safe evacuation. A different design solution might have been obtained if this had been a real project, and if more reliable data for calculating the construction costs were available.

Concluding remarks:

- The use of a fire safety engineering method must be done carefully. Misuse can easily give the wrong impression that the building is safe enough.
- a risk based verification method or design method is a necessity if consideration is taken to reliability of different components.
- the risk based verification method presented and used in this report is suitable for relative ranking of different design solutions.
- when using a fire safety engineering method in combination with a risk based verification method and a performance-based building code the cost effectiveness is clearly demonstrated.

- one weakness of the methods applied is the lack of reliable data to be used in the calculations and it is obvious that more work has to be done both in collecting and structuring data.
- using a risk based verification method as a complement takes much longer time to perform than simple engineering methods but it is a necessity and it is also economically defendable in a building of this type.

9. REFERENCES

Act (1994:847) of technical requirements for construction works etc, BVL.

Boverket 1997, Utvärdering av ändringar i byggregleringen: Brand. Boverket rapport 1997:9.

Building Regulations 94, BBR94 (BFS 1993:57, with amendments BFS 1995:65) mandatory provisions and general recommendations, The Swedish Board of Housing, Building and Planning (Boverket), Karlskrona Sweden, 1994.

Bukowski R., Status report on CIB W14 TG1, Engineering evaluation of building fire safety performance. Presented at CIB W14, Gent, 1997.

CPQRA, Guidelines for Chemical Process Quantitative Risk Analysis. Center for Chemical Process Safety of the American Institute of Chemical Engineers. New York, 1989.

Design Regulations 94, BKR 94, (BFS 1993:58, with amendments BFS 1995:18) mandatory provisions and general recommendations Swedish Board of Housing, Building and Planning (Boverket), Karlskrona, 1994.

EUROCODE 1: Basis of design and actions on structures, Part 2-2 : Actions on structures exposed to fire. ENV 1991-2-2: 1994.

Evans, D.D., Stroup, D.W., Methods of Calculating the Response Time of Heat and Smoke Detectors Installed Below Large Unobstructed Ceilings. NBSIR 85-3167, National Bureau of Standards, Gaithersburg, 1985.

Fire safety engineering in buildings; draft for development, BSI DD240, 1997.

Fire Engineering Guidelines. Fire Code Reform Centre Ltd, first edition, Sydney Australia, 1996.

Fire Engineering Design Guide, Center for Advanced Engineering, University of Canterbury, New Zealand, 1994.

Frantzich H., Fire Safety Risk Analysis of a Health Care Facility. Rapport 3085, Department of Fire Safety Engineering, Lund University, Lund, 1996.

Frantzich H., Fire Safety Risk Analysis of a Hotel. Rapport 3091, Department of Fire Safety Engineering, Lund University, Lund, 1997.

Frantzich, H., Uncertainty and Risk Analysis in Fire Safety Engineering. Report 1016. Department of Fire Safety Engineering, Lund University, Lund, 1998.

International Atomic Energy Agency (IAEA), Evaluating the Reliability of Predictions made using Environmental Transfer Models. Safety Series No. 100, Vienna, 1989.

ISO/CD 13388 Fire Safety Engineering - Design Scenarios and Design Fires, 1997.

Jönsson, R., Frantzich, H., Karlsson, B., Magnusson, S.E., Ondrus, J., Pettersson, O., Bengtson, S., Osterling, T., Thor, J. Brandskydd - Teori och praktik. Brandskyddslaget, Stockholm, 1994.

Kristiánsson, G. H., On Probabilistic Assessment of Life Safety in Building on Fire. Report 5006, Department of Fire Safety Engineering, Lund University, Lund, 1997.

Magnusson, S.E., Probabilistic Analysis of Fire Exposed Steel Structures, Lund Institute of Technology, Division of Structural Mechanics and Concrete Construction, Bulletin, 27, Sweden 1974.

Magnusson, S.E., Frantzich, H., Karlsson, B., Särdqvist, S., Determination of Safety Factors in Design Based on Performance. Proceedings of the Fourth International Symposium on Fire Safety Science, pp 937-948, Gaithersburg, 1994.

Magnusson, S.E., Frantzich, H., Harada, K., Fire Safety Design Based on Calculations, Uncertainty Analysis and Safety Verification. Rapport 3078, Department of Fire Safety Engineering, Lund University, Lund, 1995.

Marberg, P-A., Frantzich, H., Jönsson, R., Lundin, J., Rantatalo, T., Practical Design and Performance Based Regulations. J. Fire Science and Technology. ISSN 0285-9521. Vol 18. N0 1. 1998.

Nybyggnadsregler (NR), BFS 1988:18, Boverket, Karlskrona, 1988.

Ordinance (1994:1215) on technical requirements for construction works etc, BVF.

Peacock, R.D., Jones, W.W., Forney, G.G., Portier, R.W., Reneke, P.A., Bukowski, R.W., Klote, J.H., An Update Guide for HAZARD I Version 1.2, NISTIR 5410, US Department of Commerce, National Institute of Standards and Technology, Gaithersburg, 1994.

Pettersson, O., Magnusson, S.E. and Thor, J., Fire Engineering Design of Steel Structures, Swedish Institute of Steel Construction, Publ. No. 50, Stockholm, 1976 (Swedish Edition 1974).

Pettersson, O. and Ödeen, K., Fire Engineering Design of Building Structures – Principles, Design Rules Examples (in Swedish), Liber Publishers, Stockholm, 1978.

Pettersson, O. and Magnusson, S.E., Functional Approaches – An Outline, Lund Institute of Technology, Division of Structural Mechanics and Concrete Construction, Bulletin, 62, Sweden 1978.

Standard for automatic water-sprinkler-systems, RUS 120:4: The Swedish Association of Insurance Companies, Stockholm, 1987.

Standard for fire detection systems, RUS 110:5; The Swedish Association of Insurance Companies, Stockholm, 1992.

The Swedish Planning and Building Act, PBL (1987:10).

Thompson, P., Marchant, E., A Computer Model for the Evacuation of Large Building Populations. Fire Safety Journal Vol. 24, No. 2, pp 131-148, 1995.

Värdering av risk, ISBN 91-88890-82-1, Räddningsverket Karlstad, Sweden, 1997.

APPENDICES

APPENDIX 1
Swedish building regulations (BBR94, BKR94)

APPENDIX 1, SWEDISH BUILDING REGULATIONS (BBR94, BKR94)

(This appendix only contains parts of the translated Swedish building regulations.)

PARTS OF BBR 94

5 SAFETY IN CASE OF FIRE

This section contains mandatory provisions and General recommendations pursuant to Chapter 3 Section 15 and Chapter 9 Section 1 of PBL and Section 4 of BVF. Further mandatory provisions and General recommendations regarding the load bearing capacity of buildings in case of fire are given in the Design Regulations of the Board, BKR 94. *(BFS 1995:17)*

5:11 Alternative design *(BFS 1995:17)*

Fire protection may be designed in a way different from that specified in this section *(Section 5)* if it is shown by a special investigation that the total fire protection of the building will not be inferior to that which would obtain if all the requirements specified in the section had been complied with. *(BFS 1995:17)*

General recommendation: Such an alternative design may for instance be applied if the building is provided with fire protection installations *in addition* to those which follow from the requirements specified in this section. The special investigation shall be documented in the fire protection documentation in accordance with Subsection 5:12. *(BFS 1995:17)*

5:12 Documentation

Fire protection documentation shall be drawn up. This shall set out the conditions on which fire protection is to be based and the design of the fire protection. *(BFS 1995:17)*

General recommendation: The documentation should set out the fire resistance classes of the building and its components, compartmentation, escape strategy, the function of the air handling installation in the event of fire and if appropriate description of fire engineering installations, and control and maintenance schedule. *(BFS 1995:17)*

5:13 Design by calculation *(BFS 1995:17)*

If design of fire protection is based on calculations, calculations shall be based on a carefully selected design fire and shall be performed in accordance with a model which gives a satisfactory description of the problem at hand. The calculation model selected shall be stated. *(BFS 1995:17)*

General recommendation: The uncertainty in the selected input data may be illustrated by means of sensitivity analyses. (BFS 1995:17)

5:14 Control of design for escape

In buildings where there is a high risk of injury to persons, design for escape by calculation may be used only if the correctness of the calculation can be demonstrated by design control.

General recommendation: The term design control refers to control of design assumptions, construction documents and calculations. *(BFS 1995:17)*

5:2 Fire resistance classes and other conditions

General recommendation: Methods for the verification of fire resistance properties in different classes are given in advisory publication No 1993:2 of the Board, Guidelines for type approval, Fire protection.

5:21 Buildings

A building shall be constructed to Class Br1, Br2 or Br3. Classification shall take account of factors which affect the possibility of escape and the risk of injury to persons in the event that the building collapses. The possibility of escape shall be assessed in view of the height and volume of the building and the activity which shall be carried on in the building, and of the number of persons who are expected to be in the building at the same time and the likelihood that these persons can reach safety on their own.

A building where a fire entails a high risk of injury to persons shall be constructed to Class Br1. In such buildings the most stringent requirements are imposed on e.g. finishes and on load bearing and separating structures. A building where a fire may entail a moderate risk of injury to persons shall be constructed to Class Br2. Other buildings may be constructed to Class Br3.

General recommendation: Buildings of *three or more storeys* should be constructed to Class Br1.
The following buildings of *two storeys* should be constructed to Class Br1:
-Buildings containing sleeping accommodation for persons who cannot be expected to have good knowledge of the premises.
–Buildings intended for persons not very likely to reach safety on their own.
–Buildings with places of assembly situated on the second storey.

The following buildings of *two storeys* should be constructed to not less than Class Br2:
–Buildings intended for more than two flats and in which habitable rooms or workrooms are situated on the attic storey.
–Buildings with places of assembly at ground level.
–Buildings which have a building area greater than 200 m^2 and which are not divided into units not exceeding this size by compartment walls constructed to not less than Class REI-M60 (see Subsection 5:221).
-Buildings of *one storey*, with places of assembly at or below ground level, should be constructed to not less than Class Br2.

5:22 Elements of structure, materials, claddings and surface finishes

5:221 Class designations

Depending on their function, elements of structure are assigned in this statute to the following classes:

- R (load bearing capacity),
- E (integrity), and
- I (insulation).

The designations R, RE, E, EI and REI are followed by digits specifying the time requirement, 15, 30, 45, 60, 90, 120, 180, 240 or 360 minutes.

The classification may be combined with the designation

- M (where special consideration must be given to mechanical action), or
- C (for doors with an automatic closing device).

The following class designations are used in addition:

- *Noncombustible* and *combustible* material and material *of low ignitability* (combustible
- material which complies with certain requirements).
- *Ignition retardant* cladding.
- *Pipe insulation* of Class P I, P II or P III.
- *Surface finish* of Class I, II or III (of which Class I complies with the most stringent
- requirements).
- *Floor covering* of Class G.
- *Roof covering* of Class T.

5:222 Separation to a certain fire resistance class

The term *separation to a certain fire resistance class* refers to separation by means of floors and walls - inclusive of openings for services and similar and junctions with adjoining elements of structure - which comply with the requirements regarding separation specified for the class concerned. Doors and windows in elements of structure with a separating function may in certain cases be constructed

5:3 Escape in the event of fire

5:31 General

Buildings shall be designed so that *satisfactory escape* can be effected in the event of fire. Special attention shall be paid to the risk that persons may be injured by the fall of elements of structure or due to falls and congestion, and to the risk that persons may be trapped in recesses or dead ends.

General recommendation: Satisfactory escape implies either complete evacuation of all persons who are present in a building or - as may arise in e.g. institutional buildings or very tall buildings - escape by persons who are in the part directly affected by the fire to a place of safety inside the building. In the latter case it must be possible for protection against heat and toxic gases to be provided during an entire fire sequence or at least during the time which in the most unfavourable instance is required for a fire under the conditions in question to be completely extinguished. Examples of methods for the design of escape routes are given in report No 1994:10, *Design for escape*, of the Board. *(BFS 1995:17)*

5:312 Windows as escape routes

In dwellings - but not in alternative forms of dwelling -, offices and comparable spaces in a building, one of the escape routes may consist of a window provided that escape can take place safely. In assessing the situation, consideration shall be given to whether or not the equipment of the rescue service can be used for escape.

General recommendation: Windows used for emergency escape should be able to open without a key or other implement and should have a clear vertical opening not less than 0.5 m wide and not less than 0.6 m high. The sum of width and height should be not less than 1.5 m. The bottom of the window opening should be not more than 1.2 m above floor level. If the flat is larger than one room and kitchen or similar and is accessible only from a rescue road, it should have a balcony which can be reached from the rescue road.

5:313 Only one escape route

A door leading directly to a street or similar space may be the only escape route from small premises at ground level where only a small number of persons is likely to be present.

A stairway, *Tr1*, may be the only escape route from dwellings - but not alternative forms of dwelling -, offices and comparable premises in a building irrespective of the number of storeys. The stairway may not be in communication with the basement. It is stipulated that the distance between the stairway and a place of occupation inside the dwelling or office is not so large that the storey cannot be evacuated before it is blocked in the event of fire.

A stairway, *Tr2*, may under the same circumstances as those above be the only available escape route in a building of not more than eight storeys.

General recommendation: The distance to a stairway intended as an escape route should not normally be greater than 30 m.

5:314 Stairway, Tr1

The term *stairway Tr1* refers to a stairway which is constructed so that it prevents the spread of fire and fire gases to the stairway for not less than 60 minutes. The stairway shall be in communication with other spaces through a *protected lobby* which is either open to the external air or is provided with arrangements which prevent the spread of fire gases to the stairway. The protected lobby may be fitted with doors to a lower fire resistance class. Neither the stairway nor the protected lobby shall be in communication with a storey that is situated below the storey which shall be used during escape as the means of exit to the external air. A lift or an inlet opening to a refuse chute or similar shall not be placed inside the stairway.

General recommendation: Doors between the stairway and the protected lobby may be constructed to not less than Class E-C30. Doors between a dwelling or other premises and the protected lobby should be constructed to not less than Class EI-C60. If the protected lobby abuts onto a communication route, corridor or similar space in its own fire compartment, Class EI-C30 is sufficient.

5:315 Stairway, Tr2

The term *stairway Tr2* refers to a stairway which is constructed so that it limits the spread of fire and fire gases to the stairway for not less than 60 minutes. If the stairway serves a building with fewer than eight storeys, the doors to the stairway may be constructed to a lower class. The stairway shall be in communication with dwellings, working premises or other similar spaces where persons are present other than occasionally only through a space in its own fire compartment.

Spaces other than dwellings or working premises and other similar spaces where persons are present other than occasionally shall be in communication with the stairway only through a protected lobby. Such spaces shall however have access to at least one more escape route and access road for the rescue service unless this is evidently unnecessary.
Attic spaces with occupants' store rooms may be in direct communication with a stairway Tr2 through doors constructed to not less than Class EI-C60.
A lift or an inlet opening to a refuse chute or similar shall not be placed inside the stairway. *(BFS 1995:17)*

General recommendation: Doors to a stairway Tr2 should be constructed to not less than Class EI-C60. If the stairway serves a building with fewer than eight storeys, Class EI-C30 is sufficient. An attic space with small occupants' store rooms need not be provided with a second escape route or access road. *(BFS 1995:17)*

5:33 Travel distance

5:331 Travel distance to an escape route

The travel distance inside a fire compartment to the nearest escape route shall not be so great that the compartment cannot be evacuated before critical conditions arise.

5:332 Travel distance along an escape route

Along an escape route, the travel distance to the nearest stairway leading to another storey, or to an exit leading into the street or similar space, shall not be so great that escape cannot take place rapidly.

General recommendation: The greatest travel distance can be determined with regard to the activity which shall be carried on in the building. The travel distance should not normally be greater than 30 m if escape can be effected in two directions.

5:34 Access

5:341 The dimensions of escape routes

Escape routes shall be designed to be so spacious and to permit such ease of movement that they are capable of serving the number of persons for which they are intended.

General recommendation: The width of an escape route should be not less than 0.9 m. In escape routes from fire compartments intended for more than 150 persons, the width should be not less than 1.2 m.

5:36 Design conditions

5:361 Critical conditions in the event of escape

In design with respect to the safety of escape, the conditions in the building shall not become such that the limiting values for critical conditions are exceeded during the time needed for escape.

General recommendation: In evaluating critical conditions, consideration should be given to visibility, thermal radiation, temperature, noxious gases and the combination of temperature and noxious gases. The following limiting values can normally be applied:

- Visibility: level of fire gases not lower than 1.6+(0.1xH) m, where H is the height of the room.
- Thermal a short term radiation intensity of maximum 10 kW/m^2, radiation: a maximum radiant energy of 60 kJ/m^2 in addition to the energy from a radiation of 1 kW/m^2.
- Temperature: air temperature not higher than 80°C.

5:37 Special conditions

5:371 Places of assembly

Escape routes from places of assembly shall be designed for the number of persons who are permitted to be present in the premises. Escape from places of assembly shall not take place through other places of assembly.

General recommendation: If the number of persons is not known, the following assumptions may be made:

–If the premises shall be used by seated persons and the seats are placed in rows, the escape routes should be designed for 1.7 persons/m^2 net area. The gangways in the premises which are intended for the seated audience should be counted as part of this area, but the stage or dais should not.

-If the premises shall be used for both standing and seated persons, the escape routes should be designed for 2.5 persons/m^2 net area.

The escape routes in a department store or similar installation for retail trade should be designed for 0.5 persons/m^2 net area for those spaces to which the public has access.

In places of assembly or in the anterooms of these there should be signs stating the maximum number of persons who are permitted to be in the premises at the same time.

Places of assembly should have not less than three escape routes if they are intended for more than 600 persons, and not less than four if they are intended for more than 1000 persons.

Escape routes from places of assembly may be in communication with one another through intermediate foyers or similar spaces which are separated from the escape routes by construction to not less than Class EI-C30.

5:3711 Escape alarm

Places of assembly shall be provided with an escape alarm which is activated automatically or from a staffed position when a fire is indicated.

General recommendation: The escape alarm should give those who are present in the place of assembly spoken information regarding appropriate action to be taken for escape.

5:3712 Emergency lighting etc.

Places of assembly shall be provided with general lighting and emergency lighting. Stairs in places of assembly shall be provided with emergency lighting. Emergency lighting shall be provided immediately before exits to the external air. It shall be possible for the lighting needed in places of assembly in the event of escape to be switched on from one position in the premises. External escape routes from places of assembly shall be lit and provided with emergency lighting along their entire length.

5:5 Protection against the spread of fire inside a fire compartment

5:51 Requirements regarding materials, surface finishes and claddings

5:512 Surface finishes and claddings in escape routes

Surface finishes and claddings in escape routes shall be of materials which provide negligible contribution to the spread of fire.

In buildings of *Class Br1* or *Br2*, ceiling surfaces and internal wall surfaces in escape routes shall have surface finish of Class I. The surface finish shall be applied to Non-combustible material or to ignition retardant cladding.

In buildings of *Class Br3*, ceiling surfaces and internal wall surfaces shall have surface finish as follows:

a)Escape routes in hotels, institutional buildings and places of assembly shall have surface finish of Class I on ceiling surfaces and not less than Class II on internal wall surfaces. The surface finish shall be applied to Non-combustible material or to ignition retardant cladding.

b)Escape routes which are common to two or more dwellings or offices shall have surface finish of Class I on ceiling surfaces and not less than Class II on internal wall surfaces.

c)Escape routes from premises for activity which presents a fire hazard shall have ceiling and wall surfaces with surface finish of Class I applied to non-combustible material or to ignition retardant cladding.

In buildings of *Class Br1* the floor covering in escape routes shall be constructed of a material with a moderate propensity to spread fire and evolve fire gases.

General recommendation: The floor covering should be made of non-combustible material or material which is assigned to Class G.

5:6 Protection against the spread of fire and fire gases between fire compartments

5:61 Division into fire compartments

Buildings shall be divided into fire compartments separated by elements of structure which impede the spread of fire and fire gases. Each fire compartment shall comprise a room - or associated groups of rooms - in which the activity has no immediate connection with other activities in the building. A fire compartment shall not - with the exception of dwellings, stairways, lift wells and open garages - comprise spaces on more than two storeys unless the spaces are protected by an automatic water sprinkler installation or other arrangements, and it is shown by special investigation that the requirements in this section (*Section 5*) are complied with.

Each fire compartment shall be separated from other spaces in the building by elements of structure (including service penetrations, necessary supports, connections and similar) constructed to not less than the fire resistance class commensurate with the requirements in

Sections 5:6-5:8.

General recommendation: Dwellings or offices, stairways, garages, boiler rooms, refuse storage rooms, hospital wards, guest rooms in hotels, escape routes and large staff rooms are examples of self contained fire compartments. In industrial buildings it is appropriate to place in their own fire compartments spaces for activities where it is known by experience that fire may have serious consequences or is of great significance for the activity as a whole. This applies, for instance, to central heating plants, power supply installations and different types of warehouses.

5:62 The fire resistance class of elements of structure separating fire compartments

5:621 Fire resistance class

5:6211 Buildings of Class Br1

Elements of structure shall be constructed to not less than the fire resistance class set out in Table (a) below. The fire resistance class in Column 1 ($f \leq 200$) may be applied for dwellings and offices, schools, hotels, garages for cars, shops for the sale of food, residents' store rooms and comparable fire compartments. The class may also be applied for fire load intensities higher than 200 MJ/m^2 for buildings protected by an automatic water sprinkler installation or if conditions are such that a fire is completely extinguished by the action of the rescue service not later than 60 minutes after the outbreak of fire.

Walls and ceilings in a part of an attic which is converted into living or office accommodation, with not more than one storey above the attic floor, may be constructed to Class EI 30 adjacent to an attic space which is not utilised.

Element of structure	Fire resistance class for a fire load intensity f (MJ/m2)		
	$f \leq 200$	$f \leq 400$	$f > 400$
Element of structure separating fire compartments in general, and a floor above a basement	EI 60	EI 120	EI 240

Table a. Prescribed fire resistance class with respect to the separation function in a building of Class Br1.

5:6212 Buildings of Class Br2 and Br3

The elements of structure shall be constructed to not less than the fire resistance class set out in Table (b) below.

Element of structure	Fire resistance class
1. Element of structure separating fire. compartments in general	EI 30
2. Element of structure separating flats in a block of flats	EI 60

Table b. Prescribed fire resistance class with respect to the separation function in a building of Class Br2 or Br3.

5:6213 Fire resistance alternatives

Fire resistance class EI may be replaced by class E if the distance to the travel route for escape and to combustible material is sufficient to ensure that safety of escape is not reduced or the risk of fire spread is not increased.

5:6214 Doors, shutters and access panels

Doors, shutters and access panels in elements of structure separating compartments shall normally be constructed to the same fire resistance class as that which applies for the element of structure in question in accordance with the tables in Subsections 5:6211 and 5:6212.

If it can be shown that the fire and fire gas separating function is not impaired appreciably or that the risk of fire spread is evidently slight, the doors and similar may however be constructed to a lower fire resistance class, but not lower than one half of the class which otherwise applies and in no instance lower than Class E30. Doors and similar may be constructed to not lower than Class E if the safety of escape is nevertheless maintained and there is little risk of the spread of fire.

For buildings in Class Br1, doors and similar between escape routes and dwellings or offices, schools, hotels, residents' store rooms and comparable fire compartments may be constructed to not less than Class EI 30. *(BFS 1995:17)*

General recommendation: Examples of applications where the fire and fire gas separating function is not appreciably impaired or the risk of fire spread is slight are doors, shutters and access panels installed between fire compartments of low fire load intensity, < 50 MJ/m^2, or buildings protected by an automatic water sprinkler installation.

The safety of escape may be considered to be secured and the risk of the spread of fire gases may be considered slight if doors and similar are so sited that the distance between the doors and similar and escaping persons is such that the level of radiation does not exceed 3 kW/m^2 and that, within a sufficiently large protection zone in front of or behind the door or similar, there is no combustible material. *(BFS 1995:17)*

Doors and similar of non-combustible material which satisfy the requirements regarding insulation of Group 2 (previously Class A) and integrity (imperforateness) in accordance with the general recommendations *Guidelines for type approval, Safety in case of fire* (BFS 1993:2) of the Board or corresponding previous regulations, may however be used as alternatives to doors and similar of Class EI for the following applications:

a) Between a stairway and

- a basement or attic,
- a lobby or protected lobby, and
- shop, storage, warehouse or industrial premises.

b) Between a lift well which constitutes a fire compartment of its own and a lobby or corridor.

c) Between a pipe duct and an institutional building.

d) In a fire wall.

e) As a door to a flat.

Doors and similar into, or inside, escape routes shall be self closing. Doors and similar into dwellings or offices, small spaces which are normally kept locked, lift machine rooms, fan rooms and similar premises, or into premises situated above storeys where persons are present other than occasionally, need not however be self closing.
Self closing doors and similar may be fitted with a door stop provided that this automatically closes when fire gases are detected near it. *(BFS 1995:17)*

5:676 Lifts
A lift well inside a self contained fire compartment shall be designed so that fire or fire gases are not spread, from or via the lift well, to other fire compartments which are not exposed to fire.

A lift well shall be placed in a self contained fire compartment unless the lift well is situated

- entirely outside the building,
- inside or adjacent to a stairway and has doors to this or to a space in open communication with the stairway, or
- in a building whose design or construction in other respects does not provide an obstacle to the spread of fire such that increased fire safety can be achieved by placing the lift well in a self contained fire compartment.

General recommendation: The spread of fire or fire gases to other fire compartments from or via the lift well can be prevented by fire gas ventilation, by a lobby between the lift and adjacent fire compartments, or by doors imperforate to fire or fire gases.

The spaces for lift machinery and diverter pulleys may be placed in the same fire compartment as the lift well, provided that the spread of fire and fire gases from the lift machinery does not cause the limiting values for critical conditions to be exceeded in the car.

General recommendation: Electric cables for the machinery for a lift permitted to carry passengers, which in the event of power failure does not automatically proceed to the nearest landing, should be protected from the direct action of fire.

5:8 Load bearing capacity in the event of fire

5:81 General

Load bearing structures shall be designed and sized so that in the event of fire there is adequate structural safety with respect to material failure and instability in the form of local, overall and lateral torsional buckling and similar. Parts of the load bearing structure including supports, joints, connections and similar shall be designed so that collapse does not occur - during a specified period of time in accordance with the fire resistance classes for elements of structure set out in Subsection 5:82, under fire exposure conditions in accordance with Swedish Standard SIS 02 48 20 (2).

As an alternative, design of the load bearing structure may also be based on a model of a natural fire sequence in accordance with Subsection 5:83.

After a special investigation, the consequences of collapse may in certain cases be accepted. A departure may then be made from the fire resistance classes set out in Tables (a) and (b) in Subsection 5:821. In such cases care shall be taken to ensure that the safety of escape is not jeopardised and the risks for the personnel of the rescue service and environmental effects do not increase. Elements of structure for which collapse is accepted shall be so situated that they can be readily identified and observed.

General recommendation: Examples of elements of structure referred to in paragraph three are eaves, balconies and ceilings which do not have a separating function. *(BFS 1995:17)*

In some cases a lower part of a building may be constructed to a lower fire resistance class, provided that the load bearing capacity and stability of the taller part are independent of those of the lower part.

If an element of structure is required to be constructed to a higher fire resistance class with respect to its separating function, the element of structure shall be constructed to this higher class with respect to its load bearing function also. Floors which shall be constructed to a certain fire resistance class with respect to their separating function shall have a load bearing structure to not less than the same class. Walls which provide separation to a certain fire resistance class may be stabilised by floor constructions in accordance with Subsection 5:82.

5:82 Design by classification

5:821 Classes of performance

Elements of structure shall with respect to load bearing capacity be constructed to the fire resistance class prescribed in Tables (a) and (b) below. Column 1 ($f \leq 200$) in Table (a) may thus, without special investigation, be applied for e.g. dwellings and offices, schools, hotels, garages for cars, shops for the sale of food, occupants' store rooms and comparable fire compartments. Column 1 may also be applied for fire load intensities higher than 200 MJ/m^2 if the building is equipped with an automatic water sprinkler installation or if the conditions exist for a fire to be completely extinguished by the action of the rescue service not later than 60 minutes after the outbreak of fire.

If the element of structure contains combustible material, this need not be taken into consideration other than to a reasonable extent in calculating the fire load intensity. *(BFS 1995:17)*

Element of structure	Fire resistance class for fire load intensity f (MJ/m^2)		
	$f \leq 200$	$f \leq 400$	$f > 400$
1. Vertical load bearing structure and horizontal structure which provides stability for the structural frame			
a) in a building of not more than two storeys	R 60	R 120	R 240
b) in a building of 3-4 storeys			
– floors	R 60	R 120	R 240
– other load bearing structure	R 60	R 120	R 240
c) in a building of 5 - 8 storeys[1]			
– floors	R 60	R 120	R 240
– other load bearing structure	R 90	R 180	R 240
d) in a building of more than	R 90	R 180	R 240
eight storeys[1]	R 90	R 180	R 240
e) below topmost basement storey			
2. Horizontal structure which does not provide stability	R 60	R 120	R 240
3. Flights and landings in stairways	R 30	R 30	R 30

Table a. Prescribed fire resistance classes with respect to load bearing capacity for a building of Class Br1.

Element of structure	Fire resistance class for building of class	
	Br2	Br3
1. Vertical load bearing structure and horizontal structure which provides stability for the structural frame		
a) residential building	R 30	R 15
b) building other than residential building	R 30	–
c) below topmost basement storey[1]	R 90	R 90
2. Horizontal structure which does not provide stability		
a) residential building	R 30	R 15
b) ground floor in dwellings where there is a contiguous crawling space below the floor	R 30	R 30
c) building other than residential building		
3. Flights and landings in stairway below the topmost basement storey	R 30	R 30

[1] For fire load intensities higher than 200 MJ/m^2, Table (a) shall be applied.

Table b. Prescribed fire resistance classes with respect to load bearing capacity for a building of Class Br2 or Br3.

5:822 Design by testing and/or calculation *(BFS 1995:17)*
The characteristic load bearing capacity of a load bearing element of structure may be determined by

- *testing* in accordance with Swedish Standard SIS 02 48 20 (2),
- *calculation* in accordance with the same fire sequence, or
- *a combination of testing and calculation* as above.

General recommendation: Further mandatory provisions and general recommendations regarding testing and calculation are given in the Board's Design Regulations, BFS 1993:58, BKR 94.

5:83 Design based on a model of a natural fire sequence
Design may be based on a model of a natural fire sequence.

General recommendation: Further mandatory provisions and general recommendations regarding such design are given in the Board's Design Regulations, BFS 1993:58, BKR 94.

5:923 Stairways
Stairways in buildings of Class Br1 shall be provided with arrangements which facilitate escape and rescue action.

5:93 Equipment for manual fire fighting

In buildings with large differences in level, in larger buildings and in buildings where a fire is likely to spread rapidly, assume very high intensity or entail a serious risk of injury to persons, permanent equipment which facilitates fire fighting shall be provided. In buildings of more than 8 storeys rising mains for the supply of water for fire fighting shall be provided in all stairways. *(BFS 1995:17)*

General recommendation: The mains should have an outlet at least on every other storey. In buildings where there are alternative escape routes such as firemen's lifts, horizontal escape routes in institutional premises and similar, rising mains with outlets on each storey should be provided.

Both intakes and outlets should be provided with a notice in accordance with the mandatory provisions of the Swedish Board of Occupational Safety and Health regarding warning notices and warning signals at places of work, AFS 1994:47, with the wording 'Rising Main'.

Rising mains should be designed in accordance with Swedish Standard SS 3112 (1).

Panels in front of intakes should have a lock which can be opened with a firemen's key.

In spaces where a fire is likely to spread rapidly, assume very high intensity or entail a serious risk of injury to persons, internal fire hydrants should be provided. There is usually no risk in spaces protected by an automatic water sprinkler installation.

Internal fire hydrants should be constructed in accordance with SS-EN 671-1 (1). *(BFS 1995:17)*

PARTS OF BKR94

10 RESISTANCE IN CASE OF FIRE

Further mandatory provisions and general recommendations regarding the resistance of buildings in case of fire are to be found in Section 5:8 of Boverket's Building Regulations, BBR 94.

10:1 Requirements

Parts of the load bearing structure, inclusive of supports, joints, connections and similar, shall be constructed in such a way that collapse does not occur either

-within a certain period of time according to the requirements applicable to the fire resistance classes specified for elements of structure in Subsection 5:82 of BBR 94, or

-during a complete fire process, or

-during part of a complete fire process, if it can be shown by a special investigation that the safety of escape is not affected adversely and that the risks for the personnel of the rescue service and the effects on the environment are not increased.

General recommendation: In the same way as in conjunction with ordinary combinations of action, the requirements regarding safety against failure in case of fire should be differentiated in view of the consequences of failure. The factors which influence the choice of safety class in an ordinary combination of actions, namely the type and use of the building, the type of the load bearing structure or element of structure and the character of the envisaged failure, are also relevant in the event of fire. In a fire, the consequences of failure are to a high degree dependent on whether there are still people inside the building when failure occurs. This implies that the longer the period of time after the outbreak of fire during which there is a certain probability that people are present in the building or in its immediate vicinity, the more stringent should be the requirements regarding structural safety.

In *design by classification* in accordance with Subsection 5:82 of BBR 94, these conditions are taken into consideration by the fire resistance class prescribed for the application in question; this class is dependent on the use of the building, the height of the building, the magnitude of the fire load density, and the significance of the element of structure for the overall resistance of the building structure.

In *design based on a model of a parametric fire exposure* in accordance with Section 5:83 of BBR 94, the above conditions are taken into consideration by differentiating the design fire load density and the duration of the fire with regard to the application in question. In this way, the influence of the factors which affect the selection of safety class for the design resistance of the building structure in the event of fire is taken into consideration indirectly.

During a fire, considerable temperature movements may occur in the load bearing structure of the building. For frames and other statically indeterminate structures, these movements may give rise to appreciable increments to, and redistributions of, section forces and section moments, and cause cracking and other damage in e.g. columns, beams, floor constructions and walls. These effects occur not only in the elements of structure directly affected by fire but also in the building carcass outside the fire compartment in question. It is essential that these effects should be taken into consideration in design, and that the building carcass should be detailed appropriately with regard to these effects.

10:11 Factor of safety with respect to failure and instability in case of fire

The partial factor γ_n may be put equal to 1.0 irrespective of the safety class of the structure. The design load effect S_d shall be determined for the most unfavourable load combination, using the partial factor q_f for load in accordance with Table (b) in Subsection 2:321.

The design resistance R_d according to the method of partial factors shall be determined in view of the following conditions:

- Consideration shall be given to the reduction in strength at elevated temperatures and to the reductions in effective cross section due to combustion and the action of fire. In calculations, the strength and deformation properties, thermal conductivity and specific heat capacity of each material must be sufficiently well known within the temperature region concerned.

- Consideration shall be given to the changes in the properties of fasteners, connectors and similar under the action of fire.

- The value of the partial factor γ_m for materials in accordance with Subsection 2:322 may be assumed to be equal to 1.0 unless other values are specified in Sections 4 - 9.

10:2 Design by calculation and testing *(BFS 1995:18)*

10:21 Determination of resistance by classification

The characteristic resistance of a load bearing element of structure may be determined by *testing* in accordance with Swedish Standard SIS 02 48 20 (Nordic Standard NT FIRE 005, ISO 834). The element of structure is assumed to be acted upon by an external static load during the entire test period, corresponding to the intended period of fire resistance.
This load shall be adjusted so that the stresses at critical sections are the same as those which occur due to the design loads in the event of fire in accordance with Subsection 2:321. Temperature development at critical sections shall if possible be recorded during the test.
The resistance of the structure for a certain period of fire resistance shall be determined on the basis of associated values of applied action and time.
The characteristic resistance of a structure may be *calculated* on the basis of the conditions set out in Section 10:11 and the fire exposure in accordance with SIS 02 48 20 (NT FIRE 005, ISO 834). The assumptions regarding dimensions, spans, support conditions, design in other respects and mechanical moduli shall be made in accordance with the principles which are approved in design without regard to fire in accordance with Section 2.
The characteristic resistance of a load bearing structure in the event of fire may be determined by *combined testing and calculation.* The tests may be made on unloaded test objects if loading cannot be assumed to affect the behaviour of the test object. Temperature development at critical sections shall if possible be recorded during the test. On the basis of the recorded temperature curves and e.g. the measured depth of fire penetration in timber structures, the resistance can then be calculated if the relevant material data are known and verified.

10:22 Determination of resistance by design based on a model of a parametric fire exposure

Determination of the resistance of the structure on the basis of a model of a parametric fire exposure can in certain cases be made by testing. A combination of testing and calculation may also be applied. In all cases, the mandatory provisions of Section 10:21 shall apply as appropriate.

10:221 Fire load density

The design value of the fire load density shall be the value which is included in 80% of the observed values in a representative statistical material. However, in designing elements of structure which, according to Column 1 of Table (a) in Subsection 5:821 of BBR 94, shall be constructed to Class R 90, this value of the fire load density shall be increased by 50%.

Elements of structure which shall be constructed to Class R 60 or higher shall be designed for a complete fire process (inclusive of cooling), while for lower fire resistance classes design shall be based on the time indicated by the numerical value of the class designation (but exclusive of cooling).

General recommendation: Examples of characteristic values are given in the report *Fire engineering design of concrete structures*, published by the Swedish Council for Building Research, 1992.

10:222 Fire compartment temperature

The gas temperature T_t in a fire compartment is to be calculated from heat and mass balance equations (model of a parametric fire exposure). Consideration may be given to an automatic water sprinkler installation and fire gas ventilation.

Where flashover is not likely to occur and the fire will be limited in extent, the gas temperature T_t may be assumed to depend on the area and heat output of the fire, and not on the magnitude of the fire load density.

APPENDIX 2
Drawings

APPENDIX 2, DRAWINGS

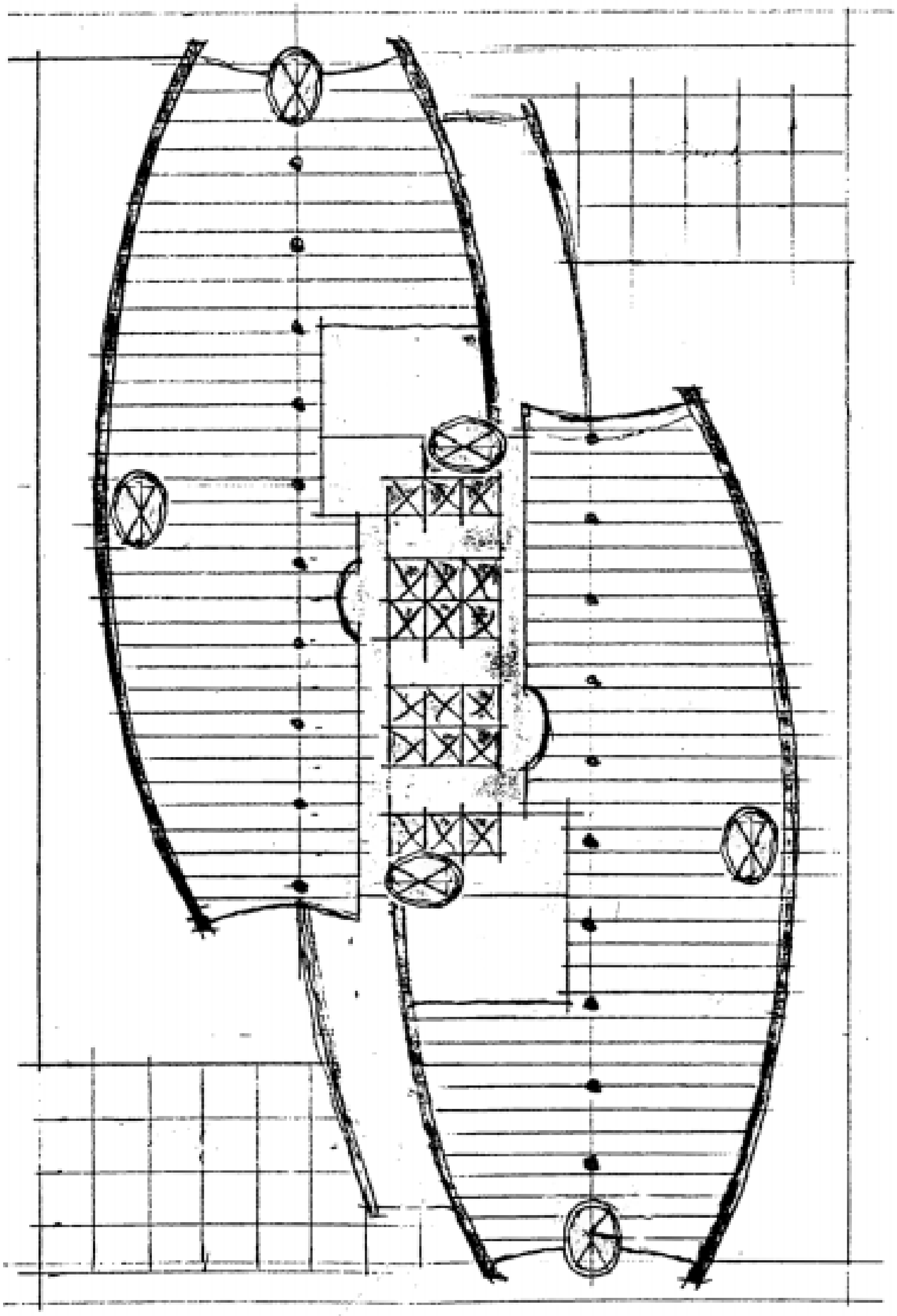


Figure A1   Plan view of the building.

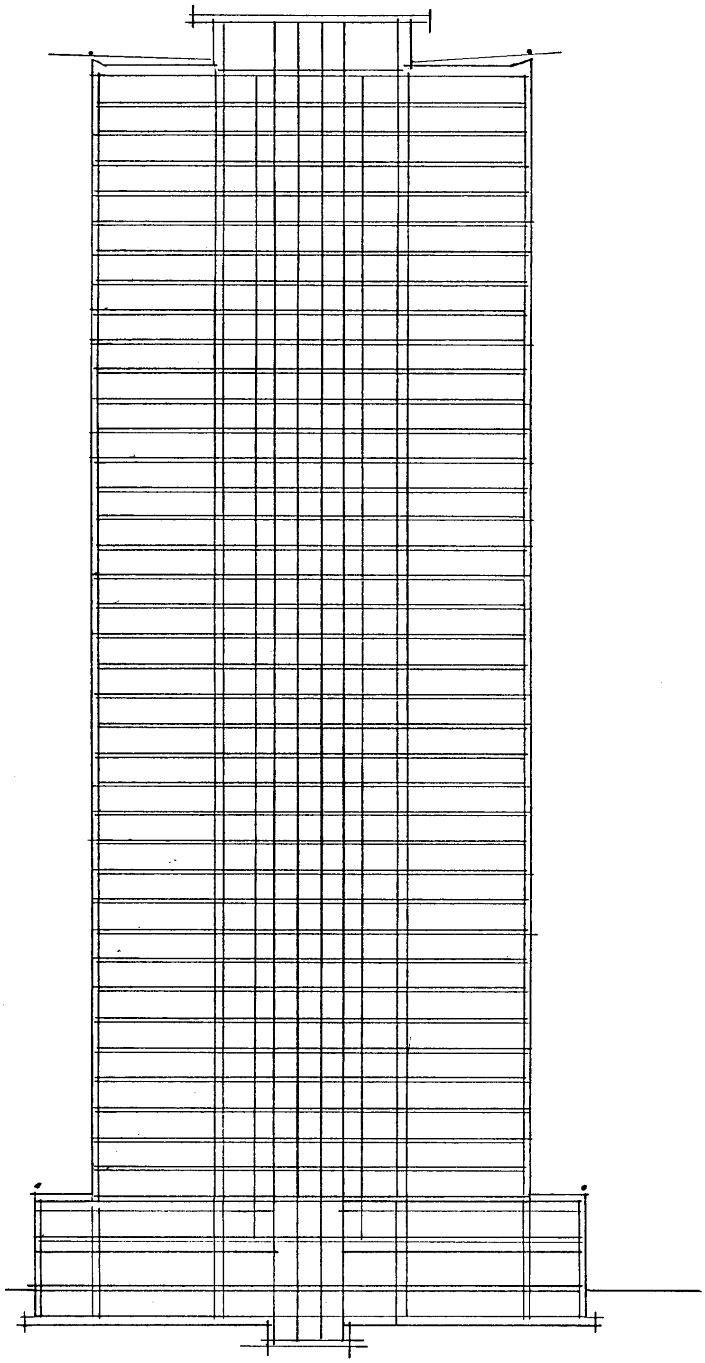


Figure A2 Section view of the building.

APPENDIX 3
Fire safety documentation

APPENDIX 3, FIRE SAFETY DOCUMENTATION

A fire-safety requirement that clearly reflects a desire for greater control and a demand for quality is that of fire-safety documentation (BBR 94, section 5:12). This represents a formal description of the fire-safety measures that have been put into effect in a new building.

The documentation is updated continually while construction is underway. Thus, when final inspection of the building takes place, the documentation should be complete. In large building projects, there is much to be clarified when initial discussions between later owners and the local authority having jurisdiction take place. Thus, continued discussions are often needed. These, together with the inspection plan submitted, helps the local authority to obtain an adequate picture of how well the building can be expected to conform to BBR 94 requirements and how the inspections are to be carried out.

The fire-safety documentation aims primarily at assessing the plans for fire safety and how these are put into effect.

It does not suffice that one simply adheres to the BBR 94 requirements. One must also describe in what manner one adheres to them.

From a societal standpoint, the most important aspect of fire-safety documentation is to report on how the building can be evacuated in case of fire. This includes the principles, the computations and the assessments that form the basis for the evacuation strategy, together with a stipulation of who is to do what. It should be noted that any computations made need to be checked for their accuracy. This includes a self-check by the construction company (BBR 94, section 5:14).

Those fire-safety aspects considered to be of central importance should be pointed out in the fire-safety documentation so as to facilitate preparing plans for inspection in accordance with the Swedish Planning and Building Act (PBL 1987:10).

Adequate fire-safety documentation should include, for example, how fire exits are to be marked, where signs to mark them are to be placed and the type of signs to be employed. In addition, the running records of operations and of maintenance (BBR 94, section 2:41), including matters of fire safety should contain written instructions on how fire-safety equipment is to be used, repaired and maintained.

Installation of the combustion-gas ventilators should be documented, providing answers to the following questions:

- What computations and what basic principles have been employed?
- What type of combustion-gas ventilators is to be used?
- Where are the ventilators to be placed?
- How is a sufficient inflow of fresh air to be provided?
- What sort of triggering device is to be installed (automatic or manual)?

Just as for the signs marking fire exits, a plan for the use and maintenance of the combustion-gas ventilators should be provided.

Fire-safety documentation can be used by a building administrator to ensure, for example that any changes made in the building do not conflict with the fire-safety measures that were planned when the building was erected. Firemen and ambulance personnel can also be helped, by having access to the information contained in the documentation. This can also serve to lessen economic liabilities in case of fire.

INSPECTION PLAN IN ACCORDANCE WITH THE PLANNING AND BUILDING ACT (PBL)

For all construction projects, some form of quality plan or quality manual should be available, containing a checklist, together with a running documentation of when, where, how and by whom inspections were carried out. The resulting document should deal with all forms of control and inspection the building project involves. The Department of Building, Housing and Planning regards it as desirable that construction companies be encouraged to perform their own controls, and that companies avail themselves of sufficient competence and expertise in this respect. This can be seen as the basis for the construction of good housing generally.

The inspection plan PBL prescribes pertains not to the soundness of a building project seen in its entirety, but only to those aspects of the project covered by the societal demands dealt with in chapter 3 of PBL, of which the Ordinance (1994:1215) on technical requirements for construction works etc (BVL) is a part. Among the societal demands involved are those contained in § 2 of BVL - Safety in case of fire.

The inspection plan which PBL calls for is to include a plan for inspection to be carried out by the building's owners, a specification of the role of an independent expert's help in inspecting the building, when inspection is to take place and who is to carry it out. Details of how inspection is to be performed can be contained in documents appended to the inspection plan. These details can include instructions by the manufacturers of safety equipment regarding building inspections, the installation of the equipment, the types of equipment authorised, the documents needed, and the like.

The checks of supporting structures that are required are listed in the Department of Housing's manual of construction regulations BKR 94, section 2:6, entitled Inspection. This provides not only a summary of inspection principles for buildings but also instructions on how inspections in the fire-safety area should be carried out.

APPENDIX 4
Description of computer models

APPENDIX 4, DESCRIPTION OF COMPUTER MODELS

A brief description of the computational programs used in the quantitative part of the analysis is presented below. For a more detailed account of the computational models, the reader is referred to the references that are cited.

CFAST

The program CFAST v2.01, Peacock et al. (1994), was employed for describing the consequences of a fire. The program computes the spread of combustion smoke through a building and the temperature of the smoke in each room. The computations are performed on the basis of conditions the user provides. The user must specify characteristics and the extent of the fire. The program contains no automatic means of assessing the fire itself. Accordingly, the size of the fire needs to be assessed separate from the program each time the program is used. In the study presented here the consequences of so-called alfa t2 fires varying in the speed with which they spread are computed. All consequences are computed as a function of time. The levels of the variables that are computed are used to determine the length of time until critical conditions are reached.

CFAST only deals with activation of the sprinklers in terms of their effect of slowing down development of the fire. Since the question of how a fire is affected by sprinkler action has not yet been adequately investigated, only estimates of sprinkler effects based on fire-engineering experience are employed.

DETACT-T^2

Detact-t^2, Evans et al. (1985) was used to determine detection times for the smoke detectors, as well as activation time for the sprinklers. The program computes the times on the basis of figures concerning the speed with which the fire spreads and which the user provides. These figures are the same as those employed for the CFAST computations.

SIMULEX

Modelling of the movements of people out of the rooms affected by fire was carried out using the program Simulex 2.0 (Thompson et al. 1995). The program computes the movements of persons within the building from the time that people begin leaving the rooms. Each person is dealt with separately, the person’s movements adjusted to the conditions existing at the time in terms of crowding and formation of queues. The time computed for evacuation of a room is thus based both on the distances to be covered to reach an exit and the formation of queues there. Persons are considered as being located in each of the rooms of the building and as starting their movements towards the exits either simultaneously or after a certain delay. In the present case, they are assumed to start simultaneously. The reaction times the persons show are dealt with separately in computing the risks.

APPENDIX 5
Modelling the design fire scenario

APPENDIX 5, MODELLING THE DESIGN FIRE SCENARIO

In modelling the design fire scenario and in calculating values connected to that, standard references were used. In this report most of the values are from the draft BSI guide (1997). Of course several of the values could be questionable, but since the report is not a research report no discussion of these values have been included.

Calculations of smoke filling, temperatures and detection times have been done with commonly used engineering computer programmes as described in appendix 4, and by standard praxis as described in different handbooks (Jönsson et al 1994, Fire Engineering Guidelines 1996, ISO 1997).

The design fire scenario has been derived from guidance in handbooks (mainly BSI 1997), and from the sensitivity study presented in this appendix.

GENERAL CONDITIONS AND ASSUMPTIONS

Each floor consists of a lobby in the middle of the building and two areas intended for office spaces. The office floor is divided into a number of 'fictive' rooms with large openings between them, to model the smoke transport more accurate. The office floor is divided according to the drawing in figure A.3

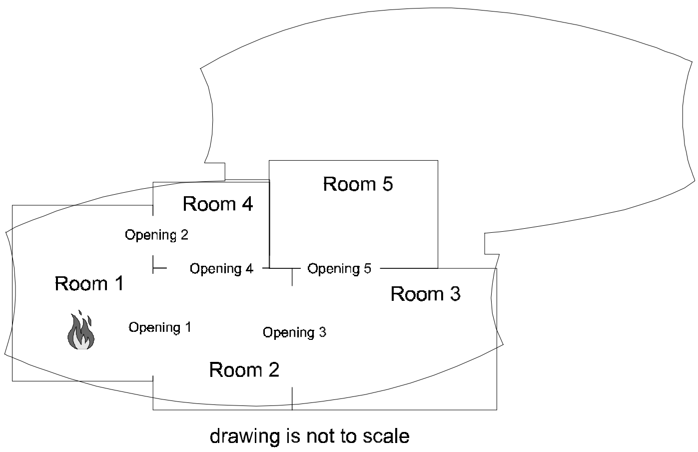


Figure A.3 Room configuration for CFAST.

Room nr	width × length × height
1	20m × 20m × 3m
2	15m × 20m × 3m
3	25m × 15m × 3m
4	12m × 8m × 3m
5	20m × 10m × 3m

Opening nr	width × height
1	15m × 2.7m
2	12m × 2.7m
3	20m × 2.7m
4	7.5m × 2.7m
5	4m × 2.1m

Table A1 Room configuration data for CFAST.

The floor is made of concrete, walls and roof are insulated by gypsum.

A fire when sprinklers are activated is modelled in the following way:
The fire burns normally until the sprinkler activates. When the sprinkler activates the rate of heat release is reduced by 80% after one minute (Jönsson et al 1994).

DESIGN FIRE

Rate of fire growth: αt^2, $\alpha = 0.012$ kW/s^2 (medium) (BSI guide 1997).

Suggested heat release rate per unit area: 250 kW/m^2 (BSI 1997).
Max rate of heat release is assumed to be 4 MW. That corresponds to a burning area of 16 m^2. It is possible for the fire to grow further since more fuel is available, but it is not likely in the time period studied here.

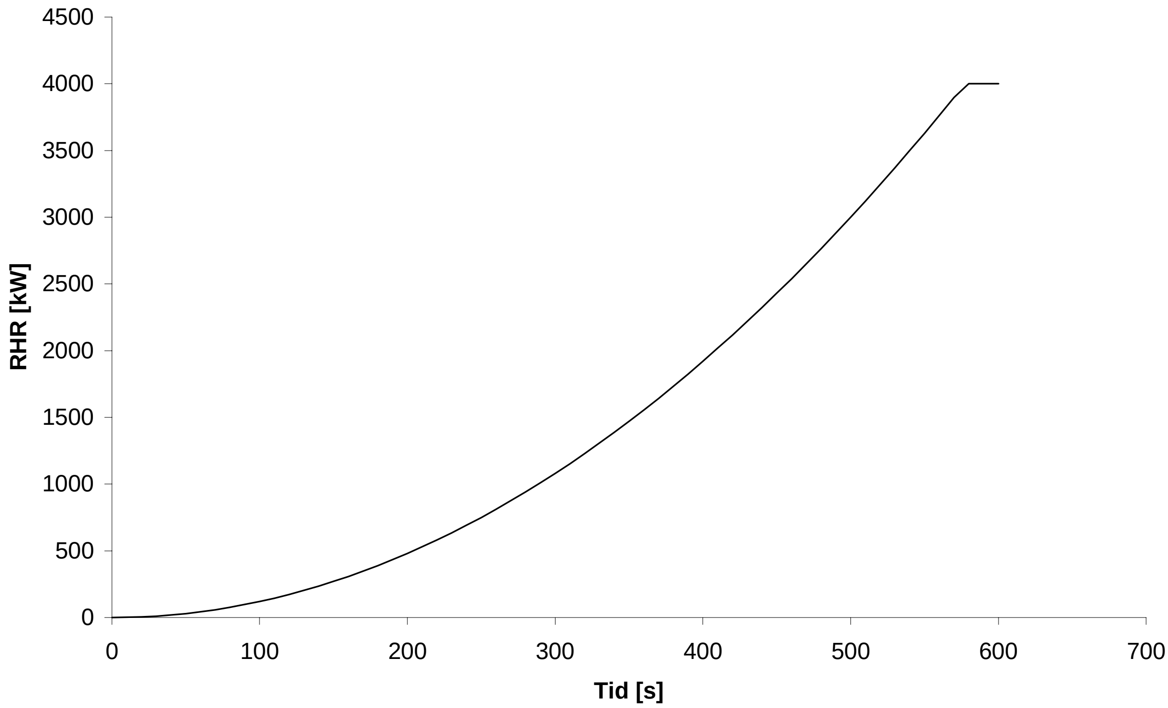


Figure A4 Design fire, α = medium and Q_{max} = 4 MW.

The same design fire is used for the restaurant and the office floors according to (BSI 1997).
Position of the fire is in the middle of room1 (figure A.3).

SENSITIVITY ANALYSIS

It is impossible to define the design scenario before knowledge about the sensitive parameters is collected. Approximations as room configuration for CFAST, RHR of design fire, origin of fire, ventilation conditions, leakage area are well known to have impact on the simulation result. A thorough sensitivity analysis was carried out and conservative assumptions where made for the uncertain parameters used as input data.

SPRINKLER ACTIVATION TIME

Sprinkler activation model detact-t2 (Evans et al 1985))
T_a = 20 °C
α = medium
RTI = 50 $m^{1/2}s^{1/2}$ (fast response)
ΔT = 68 °C
Distance between sprinkler heads = 4 m (RUS 120:4 1987)
t = 234 s (design value)

(α = slow => t = 399 s, α = fast => t = 144 s)

SMOKE ALARM ACTIVATION TIME

T_a = 20 °C
α = medium
RTI = 0.5 $m^{1/2}s^{1/2}$ (BSI 1997)
ΔT = 13 °C (BSI 1997)
Distance between detectors = 10 m (RUS 110:5 1992)
t = 185 s (design value)

(α = slow => t = 317 s, α = fast => t = 113 s)

APPENDIX 6
Evacuation calculations

APPENDIX 6, EVACUATION CALCULATIONS

GENERAL CONDITIONS AND ASSUMPTIONS

The evacuation calculations have been performed using the computer program Simulex (see appendix 4) and simple hand calculation methods. The hand calculation uses the flow of 1.2 person/s in the stairs, and 1.2 person/s through a door (effective width 1.0 m). The walking speed is 1.3 m/s. The critical factor in the hand calculation is the flow through the door opening.

It is assumed that 200 persons are on each floor, which corresponds to 0.1 person/m^2. In the restaurant floor the number of 800 persons are used. The persons are evenly distributed in the two parts of each floor. Since the exact floor layout has not been determined some approximations have been made.

Three different general scenarios have been studied:

- a detailed study of the evacuation of one office floor
- a summary study of phased evacuation of five office floors
- a detailed study of a simultaneous evacuation of the restaurant floor

In the evacuation of one floor it is assumed that a fire starts in one part of the floor, and that the whole floor is evacuated. To be able to obtain a design value for the travel time needed to evacuate a floor different alternatives are examined. These are assuming that doors are blocked in the part where the fire starts. The distribution of people and how they choose exits. The alternatives and results from both hand calculations and Simulex simulations are shown in the tables below. From the results a conservative value is chosen as design value.

In the Simulex simulations different modes have been tested on how people choose exits. Two extremes can be found. One is when you let the same number of people go to each exit, and the other when you let the people choose the closest exit. In the calculations results are shown to be somewhere in between, since people tend to go to the exit where they entered the floor. This is more truth the less familiar they are. In all calculations even distribution of people has been used. The input to the computer simulations is not given in this report.

EVACUATION OF OFFICE FLOOR

n.a. = exit not available in the design alternative
x = exit blocked by fire

<u>Standard method</u> (staircase 1,2,3,4,5 and 6 available)

Alternative	Exit 1	Exit 2	Exit 3	Exit 4	Exit 5	Exit 6	Hand calculation	Simulex
1	25	25	50	50	25	25	41 s	71 s
2	x	33	58	58	25	25	48 s	6 s
3	x	17	79	79	13	13	66 s	69 s

Table A2 Travel time for different alternatives in the the standard method.

Design value 70 s

Alternative standard method (staircase 1,3,4, and 5 available)

Alternative	Exit 1	Exit 2	Exit 3	Exit 4	Exit 5	Exit 6	Hand calculation	Simulex
1	33	n.a.	66	66	33	n.a.	69 s	69 s
2	x	n.a.	92	92	16	n.a.	83 s	78 s

Table A3 Travel time for different alternatives in the alt. standard method.

Design value 80 s

Fire safety engineering method A

Same alternatives as alternative standard method => design value 80 s.

Fire safety engineering methods B and C (staircase 3 and 4 available)

Alternative	Exit 1	Exit 2	Exit 3	Exit 4	Exit 5	Exit 6	Hand calculation	Simulex
1	n.a.	n.a.	100	100	n.a.	n.a.	100 s	77 s

Table A4 Travel time in Fire safety engineering methods B and C.

Design value 100 s

APPENDIX 7
Reliability of technical systems

APPENDIX 7, RELIABILITY OF TECHNICAL SYSTEMS

The possibilities for assessing the reliability of a technical system today are rather poor. In most fire safety planning it is simply assumed that a system will function 100 %. Such, of course, is not the case. Due to lack of more adequate information on this in the present case, fairly conservative figures were used in the computations. Although this may seem to be disparagement on our part of the technical systems involved, it was considered unreasonable to assume a particularly high degree of reliability as long as no more adequate basis for assessing it was available. Greater reliability can, of course, be expected of a technical system if an appropriate program of controls is carried out. However, merely affixing to a system a statement that the latter should be checked on once a year is not sufficient; one must also see to that such controls are performed.

After the risk analysis had been carried out, new information regarding the reliability of fire safety equipment became available. An American project of several years' duration carried out at NIST had just been completed, yielding a database which includes reliability data. Results obtained from a large number of fires had been evaluated in that project. In the present investigation, the values we employed were found to for the most part not deviate much from those obtained in the American study. Among the reliabilities available from the American study, the following can be cited:

- Sprinklers in commercial and institutional buildings: 0.95
- Smoke detector systems in commercial buildings: 0.75
- Smoke detector systems in institutional buildings: 0.85

Although no detailed report of the American study is available as yet, Bukowski (1997), the length of time during which data collection was carried out there suggests the conclusions drawn to have a substantial basis. Nevertheless, since that study relates to conditions in the U.S., the figures obtained there should be viewed with caution.

APPENDIX 8
Event trees of the design alternatives

APPENDIX 8, EVENT TREES OF THE DESIGN ALTERNATIVES

The average risk is measured in number of people affected by critical conditions, given that fire occurs.

Standard method

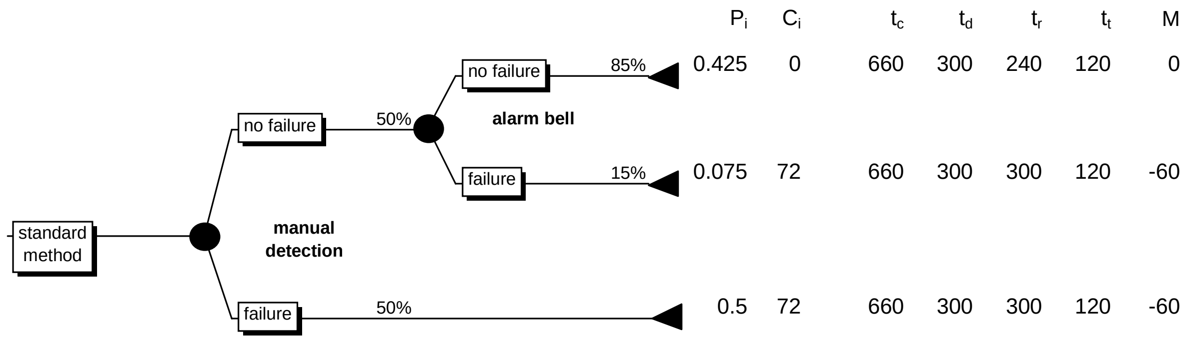


Figure A5 Event tree for standard method design.

Average risk: 41 affected / fire

Alternative standard method

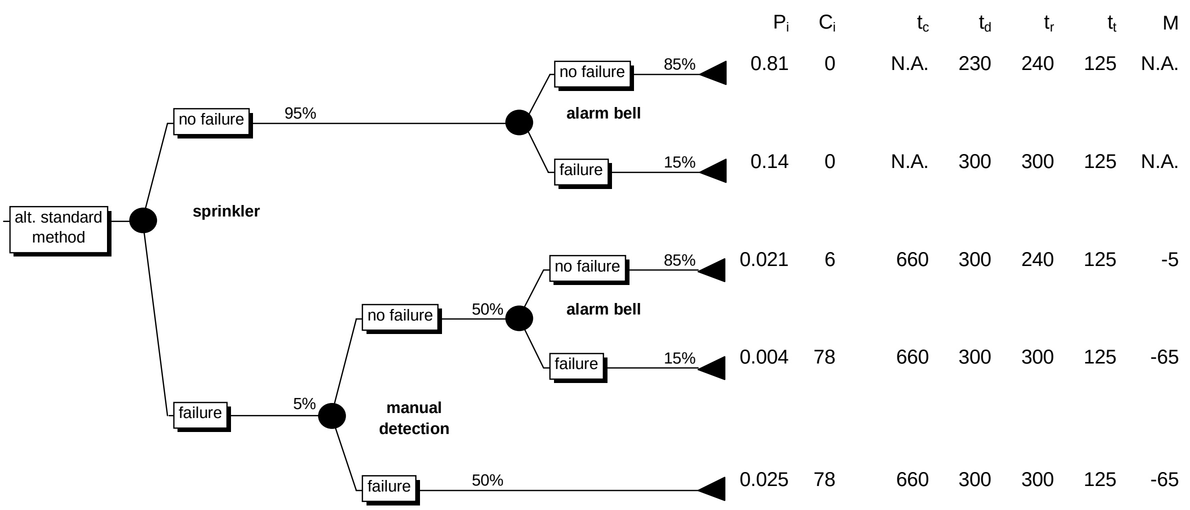


Figure A6 Event tree for alternative standard method design.

Average risk: 2.4 affected / fire

FSEM A

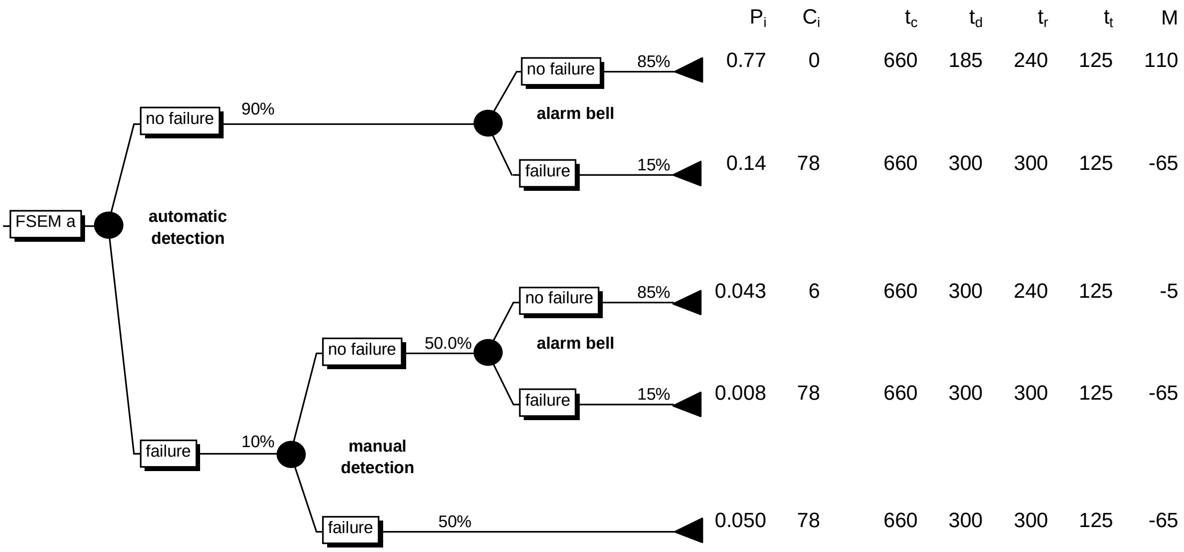


Figure A7 Event tree for Fire Safety Engineering Method A design.

Average risk: 15 affected / fire

FSEM B

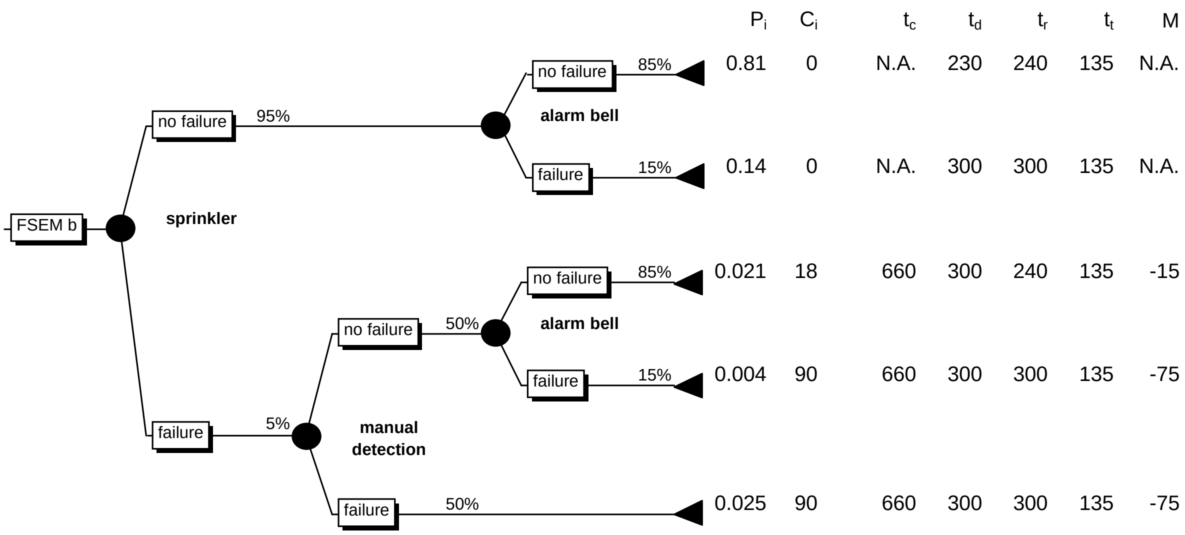


Figure A8 Event tree for Fire Safety Engineering Method B design.

Average risk: 3.0 affected / fire

FSEM C

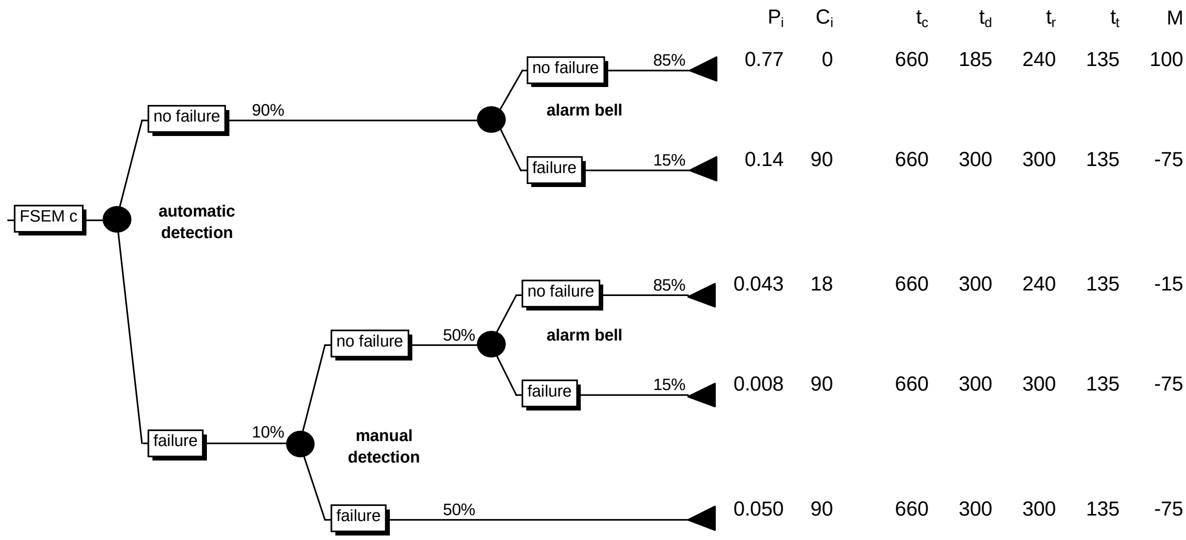


Figure A9 Event tree for Fire Safety Engineering Method C design.

Average risk: 18 affected / fire

Restaurant

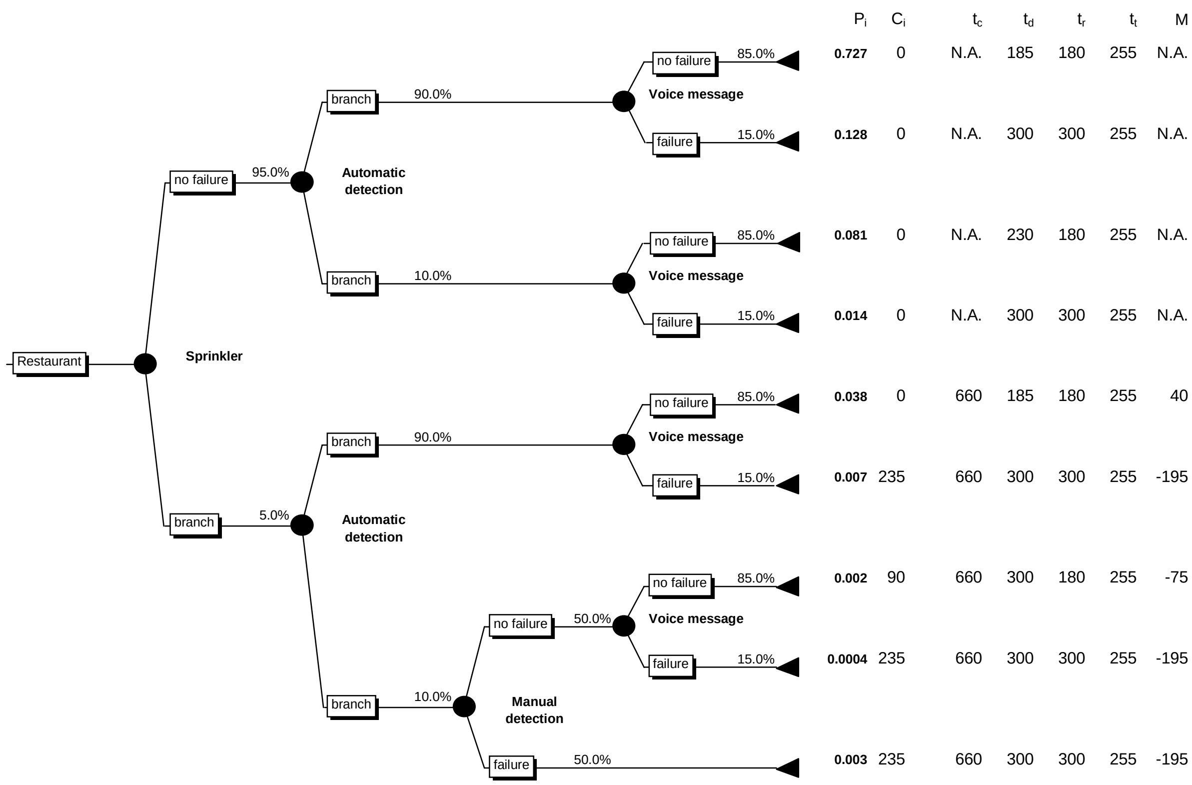


Figure A10 Event tree for Restaurant.

Average risk: 2.5 affected / fire