European Commission

technical steel research

Steel structures

Competitive steel buildings through natural fire safety concepts

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SUMMARY

The objective of the research project is to establish a more realistic and more credible approach to analysis of structural safety in case of fire that takes account of active fire fighting measures and real fire characteristics. The European Research work was sponsored by the ECSC and entitled the "Natural Fire Safety Concept". It started in June1994 and ended in December 1998. It has been undertaken by 11 European partners and is co-ordinated by ProfilARBED-Research.

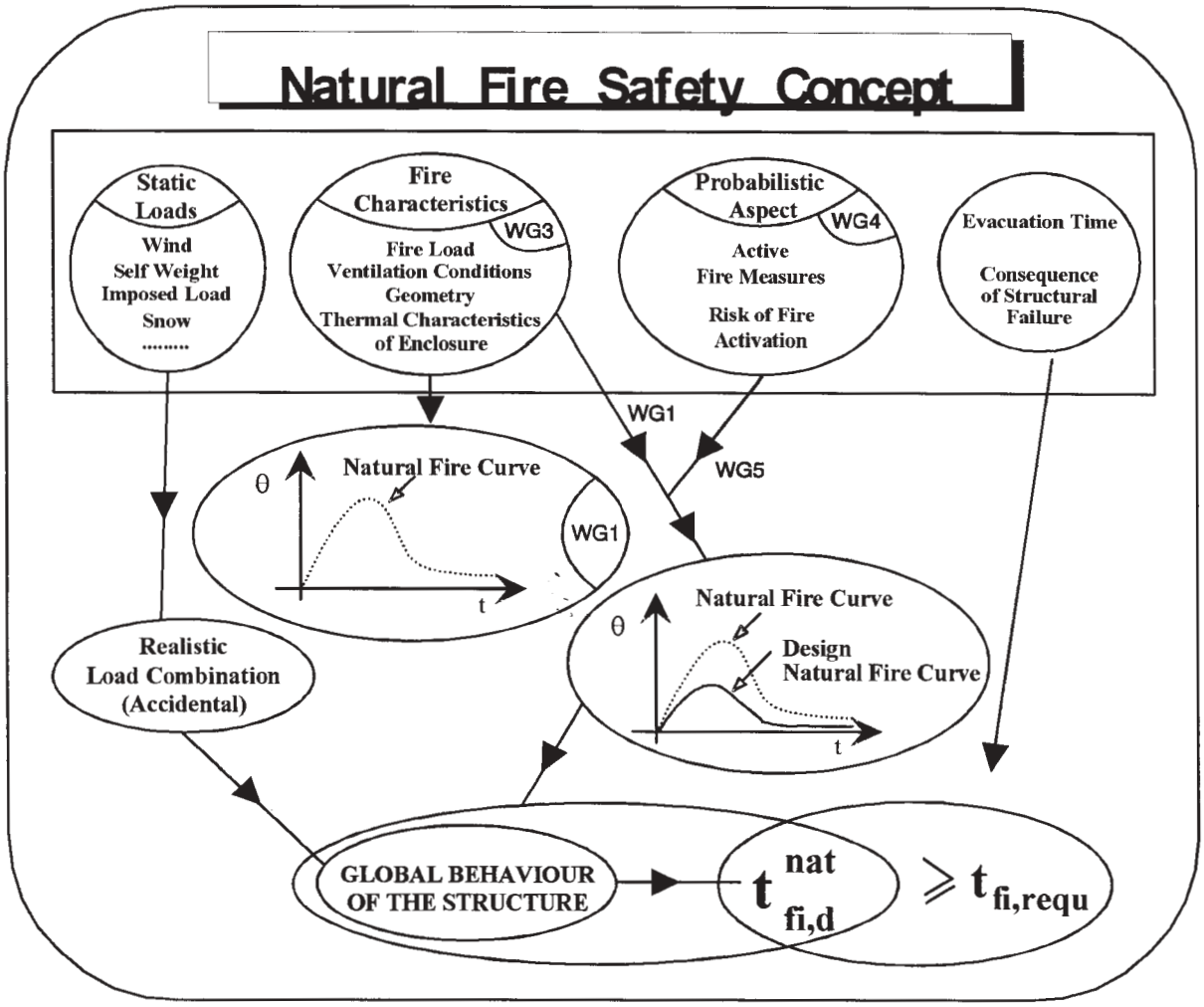

Figure A: General guidelines of the research " Natural Fire Safety Concept "

The research has developed a procedure that:

- takes into account the building characteristics relevant to fire growth: fire scenario, fire load, pyrolysis rate, compartment type, and ventilation conditions (see report of WG3);

- quantifies the risk of fire start and considers the influence of active fire fighting measures and occupation type; this risk analysis is based on probabilities deduced from databases of real fires from Switzerland, France, Finland, and United Kingdom (see report of WG4);

- deduces from the previous step design values for the main parameters such as the fire load (see report of WG5);

- determines the design heating curve as a function of the design fire load that takes implicitly into account the fire risk and therefore the fire fighting measures (see report of WG1);

- simulates the global behaviour of the structure submitted to the design heating curve and the static load in case of fire;

- deduces the fire resistance time $t_{fi,d}^{nat}$; this may often be infinite such that the structure is able to support the loads from the beginning to the end of the fire; and

- verifies the safety of the structure by comparing the fire resistance time $t_{fi,d}^{nat}$ with the required time depending of the evacuation time and the consequences of the failure.

This new concept has been applied to real projects

- Basket-Ball Hall in Pepinster (Belgium)
- Luxemburg Airport (Grand-Duchy of Luxemburg).
- Law Courts of Nantes (France).
- Building: Museum and Exhibition hall in URBINO (Italy).
- Office Building in Bilbao (Spain).
- Office Building "Langenthal", (Switzerland).
- Schools « Geesseknäppchen » in Luxemburg (Grand-Duchy of Luxemburg).

This new approach should lead to both financial benefits and better safety guidance. Hence, examples of its use should become more numerous. Less money will be wasted in attempts to guarantee resistance of structures subjected, for instance, to two hours of a wholly unrealistic ISO (or ASTM) fire. Instead, it will be evident that it is much better to identify the active fire fighting measures that provide protection for people, such as detection, alarms, automatic alarm transmission to fire-fighters, smoke exhaust systems, and sprinklers.

If the safety of people is ensured in an optimal way, the structure itself can also benefit from those measures that aim to save occupants. Hence, the further costs needed to guarantee its stability in case of fire are strongly reduced and, in some cases, even reduced to zero.

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1 INTRODUCTION

The fire safety building is an important factor which has to be taken into account from the beginning of a project and which can influence the choice of a material or a construction system. During the years 60 some dramatic fires as for instance the fire of the supermarket "Innovation" in Bruxelles which made more 300 dead implied a lot of new regulations everywhere in Europe

These regulations concern:

- The escape of the people: some standards specify the number of emergency exits, the characteristics of the exit signs, the number of staircases, the width of the doors, ...
- The fire spread: there are clauses limiting the size of compartments, defining the minimum sill heights of the windows to avoid fire spread from one floor to the upper one, defining the fire resistance of the compartment walls and the fire doors..
- The fire resistance of the structure: R30, 60, 90 or 120 and
- The active fire fighting measures like hand extinguishers, smoke detectors, sprinklers

However, up to very recently, there was no link, no connection and no trade-off possible between these different fields. The fire resistance requirements of the structure of a building were independent of the presence of a system of detection, smoke evacuation or sprinkler.

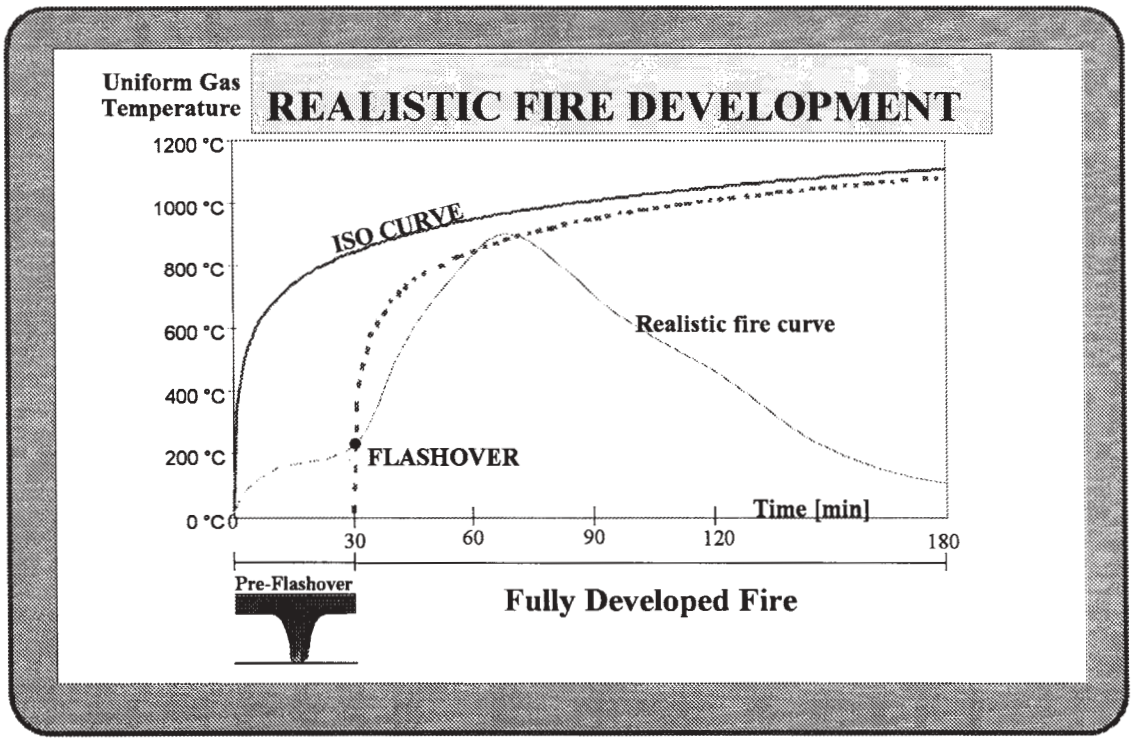


Figure 1.1 : Iso-Curve

Moreover the structural fire resistance requirement of a building were based on a standard heating curve called ISO curve.

At the beginning, the only possibility to determine the fire resistance of a building element was to perform a test in a laboratory. The element is subjected in a furnace to an increase of gas temperature according to the ISO curve with about 500°C after only 3 minutes, 800°C after 30 minutes and more than 1000°C after 90 minutes.

However this ISO curve is very different from a real fire (see Figure 1.1)

- The whole period of pre-flashover fire is completely neglected.

- There is only one ISO curve for all the types of building, whatever the fire load or the ventilation conditions are. It is assumed that the whole compartment is heated even if the compartment is huge

- The Figure 1.2 shows the ISO curve compared to about 50 fire tests made in Laboratory with fire load of 20 to 45 kg of wood/m². Opposite to the ISO curve used in standard tests, the natural fire curve shows a maximum temperature followed by a descending branch corresponding to the fact that the available materials have been consumed.

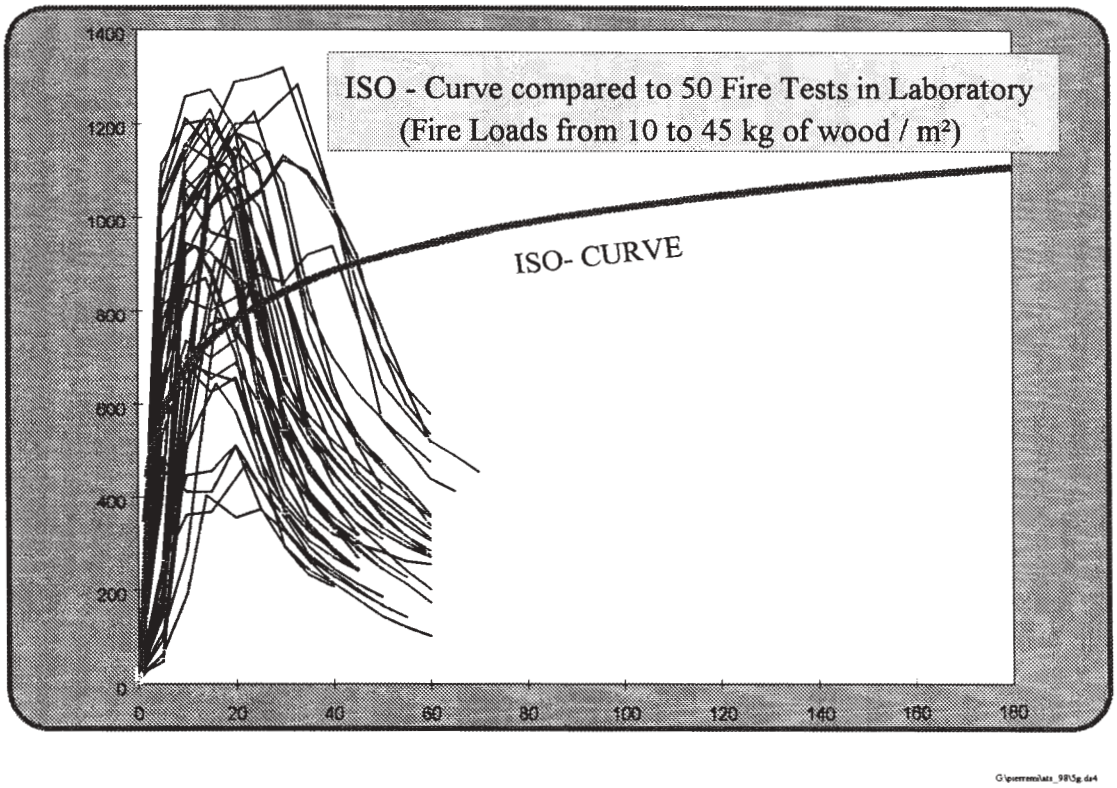
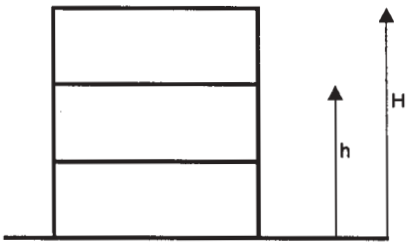


Figure 1.2 : Natural Fire Curves

Minimum Periods (minutes) for elements of structure

in the following building types									according to the regulations of									
Building type	n	h	H	X	L	b	x(*)	S	B	CH	D	F	I	L	NL	FIN	SP	UK
Industrial Hall	1	0	10	20	100	50	2	YES	0	0	0	30 *2	0/60 (7)	0	0	0	-	0 *1
								NO	0	(1) *3	(1)	30 *2	30/90 (7)	0-60	0	0	-	0 *1
Commercial center and shop	1	0	4	500	80	80	4	YES	0	0	0	0 H 30 V	60/90 (7)	30	0	0	90	0 *1
								NO	(1)	(1) *3	(1)	30	90/120 (7)	(3)	0	30	90	0 *1
Dancing	2	5	9	1000	60	30	4	YES	0	0	(2)	60	(8) (9)	30	0	60 (4)	90	30
								NO	0	30	90	60	60	30	0	60 (5)	90	60
School	4	12	16	300	60	20	4	YES	60 (6)	0 30 *3	(2)	60	(8) (10)	90	60	60 (4)	60	60
								NO	60 (6)	60	90	60	60	90	60	60 (5)	60	60
Small rise Office Building	4	10	13	50	50	30	2	YES	60 (6)	0 30 *3	(2)	60	(8) (9)	90	60	60 (4)	60	30
								NO	60 (6)	(1) *3	90	60	60	90	60	60 (5)	60	60
Hotel	6	16	20	60	50	30	2	YES	60 (6)	30 60 *3	(2)	60	(8) (11)	90	60	60 (4)	90	60
								NO	60 (6)	60	90	60	60	90	60	60 (5)	90	60
Hospital	8	24.5	28	60	70	30	2	YES	120	60	(2)	60	(8) (12)	90/120	120	60 (4)	120	90
								NO	120	90	90	60	120	120	120	60 (5)	120	90
Medium rise Office Building	11	33	37	50	50	30	2	YES	120	60 90 *3	(2)	120	(8) (9)	90	60	120 (4)	120	120
								NO	120	90	90	120	90	120	90	120 (5)	120	(3)
High rise Office Building	31	90	93	100	50	50	2	YES	120	90	90	120	(8) (9)	120	90	120 (4)	120	120
								NO	120	90 (3)	(3)	120	120	(3)	90	120 (5)	120	(3)

n = Number of storeys, ground level included
h = Height of top floor above ground
H = Height of the roof above ground level
X = Number of people to be evacuated by storey
L = Length of the compartment
b = Width of the compartment
x = Number of exit routes (* indicate your requirement, in case of no requirement the values beneath may be considered)
S = Sprinkler



(1) compartment size too large
(2) no regulation adopted
(3) not allowed
(4) q > 600 MJ/m² floor
(5) q < 600 MJ/m² floor
(6) new buildings + extension or structural charges of existing buildings
(7) Periods usually required by local authority (there'snt still national regulations)
(8) Sprinkler is a possible alternative to other requirements (case by case by authority)
(9) Required for q > 920 MJ/m²
(10) Required in underground rooms for q > 550 MJ/m²
(11) Required over 1000 beds
(12) Required over 300 beds

*1 Roof structure & structure only supporting roof requires no fire resistance. Therefore single storey building structure normally has no requirement.
*2 If H < 10m : no requirements (R0)
*3 To be checked with SIA Doc 81

For FINLAND: for load bearing structures, not for separating structures
For FRANCE : H = horizontal roof structure
V = column

Table 1.1

The present structural requirements based on the ISO curve can be seen on the Table 1.1 for different types of buildings. The requirements depend on the building height and on the occupancy of the building.

In fact there are 4 ISO curves which may be required:

- The ISO curve with a maximum at 30 minutes,
- the ISO curve with a maximum at 60 minutes,
- the ISO curve with a maximum at 90 minutes,
- the ISO curve with a maximum at 120 minutes.

By imposing one of these 4 curves in the present prescriptive based codes, the Authorities try to translate in terms of ISO fire duration, the following physical phenomena:

- Fire (Fire occurrence probability, Fire spread, Fire duration, Fire load (amount and distribution), Power of the Fire (maximum RHR in kW))
- Ventilation conditions
- Fire compartment (type, size, geometry)
- Type of the structural element
- Evacuation conditions
- Safety of the rescue teams
- Risk for the neighbouring buildings
- Active fire fighting measures

For instance in case of sprinkler the Table 1.1 shows that the present requirements with or without sprinkler system are identical except for very few cases (commercial centre in France or school in Switzerland) where the sprinklers enable to choose the ISO curve with a lower maximum duration.

This translation has been based on historical considerations, experience, real fire lessons and mainly expert judgement

In order to consider all these physical factors in a systematic way, this European Research entitled "Natural Fire Safety Concept" started in 1994. This research has been performed by 10 European partners and has been co-ordinated by ProfilARBED-Research.

The aim is thus to establish a more realistic and more credible approach to analyse the structure safety in case of fire which includes, amongst other, the active fire fighting measures and the real fire characteristics.

2 OVERVIEW OF THE RESEARCH

The standard ISO curve of the present regulations is too simple, unrealistic and leads to uneconomic situations without guaranteeing a safety proportional to the invested money.

The first result of the research is a simulation of the fire which is more sophisticated and more realistic but which remains practical.

In order to simulate a fire in a building and its effect on the structure of this building, you need to define the rate of heat release (RHR) given in kW as function of time. At the beginning the fire start small, produces a little of kW and afterwards it spreads. The fire spread velocity depends on the type of building occupation. The buildings are classified into 4 categories according to the fire spread velocity: low, medium, fast and ultra-fast (see Figure 2.1 and Table 2.1).

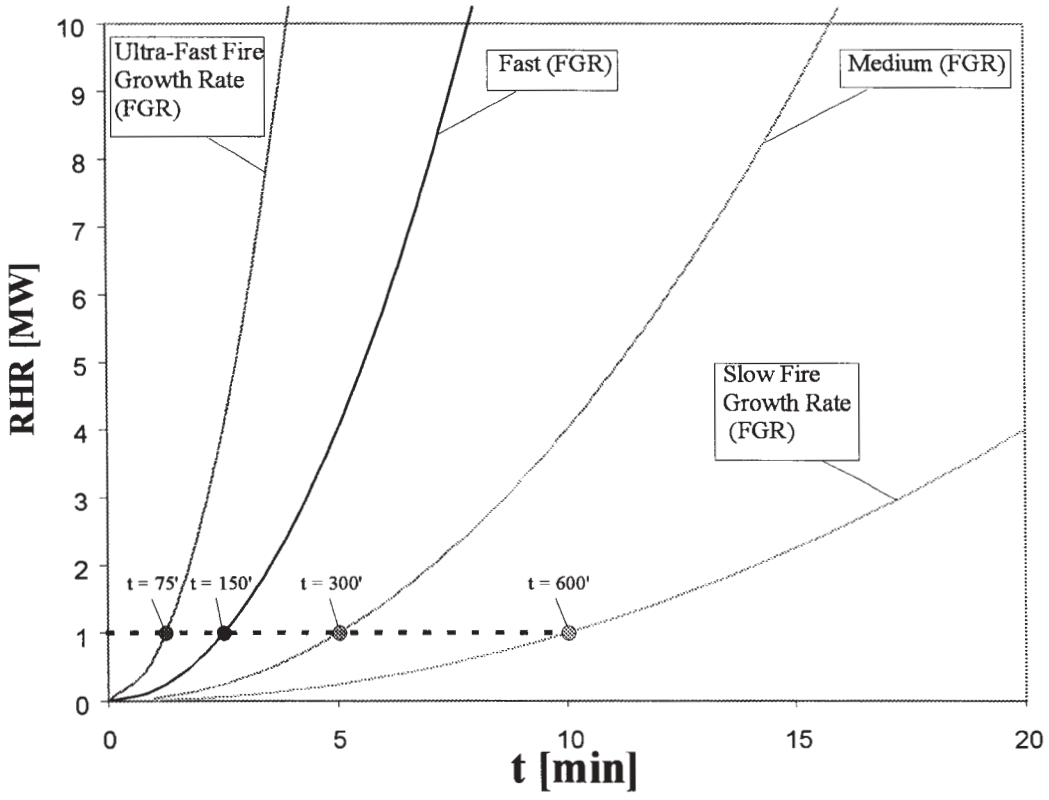


Figure 2.1 : Rate of Heat Release in the growing phase

Occupancy	Fire Growth Rate	RHR_f [kW/m²]	Fire Load $q_{k,f}$ 80% fractile [MJ/m²]
Dwelling	Medium	250	948
Hospital (room)	Medium	250	280
Hotel (room)	Medium	250	377
Library	Fast	500	1824
Office	Medium	250	511
School	Medium	250	347
Shopping Centre	Fast	250	730
Theatre (movie/cinema)	Fast	500	365
Transport (public space)	Slow	250	122

Table 2.1 : Fire Growth Rate, Fire Loads and RHR_f for different buildings

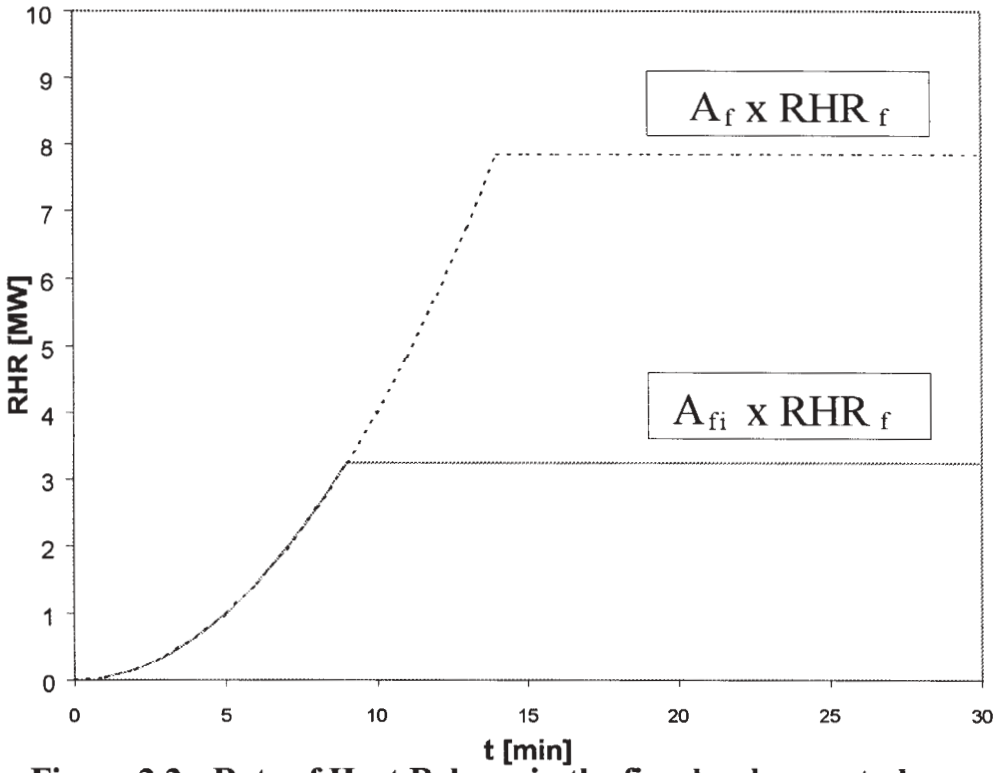


Figure 2.2 : Rate of Heat Release in the fire development phase

The fire power increases up to a maximum which corresponds to the RHR maximum per m^2 which depends on the building type (see Table 2.1), multiplied by the fire area (see Figure 2.2). This surface is the whole compartment area (A_f) or, in some cases, it is only the surface where the fire load is localised (A_{fi}). The fire remains localised for instance in case of station halls, parking, large compartments with a non-uniformly distributed fire load.

For instance the stability of the steel structure of the new airport of Luxembourg (see Annex 2) has been studied on the basis of a localised fire. The size of the compartment, the size of the maximum fire in the worst scenario, the height of the compartment and the smoke exhaust system make impossible the fact to obtain a flash-over or a compartment fully engulfed by the fire or the smoke

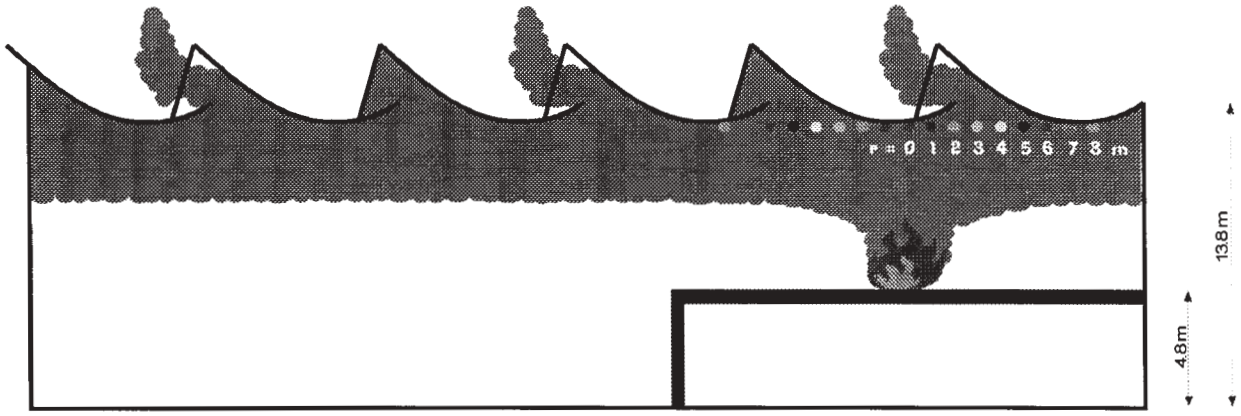


Figure 2.3 : Extension of the Airport of Luxembourg – Smoke Zone and Temperature Field

The localised fire produces a smoke zone of a constant height and a heating of the structure depending on the distance from the fire (see Figures 2.3 and 2.4).

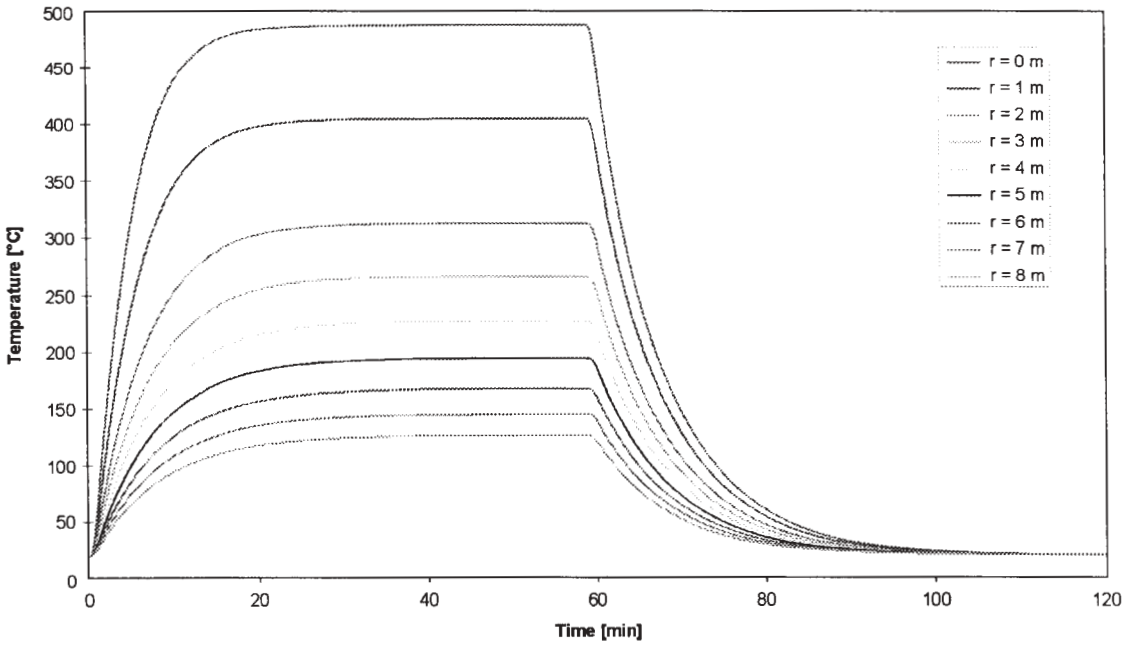


Figure 2.4 : Tefinaf Calculation – Temperature of the steel as a function of the time for different radial distances.

The height of the smoke zone and the temperatures of the hot gases at the level of the steel structure at different distances from the fire have been calculated by the model TEFINAF established in the scope of the research. The model TEFINAF combines a two-zone model which provides the height and the mean temperature of the hot zone and the Hasemi formula which gives the temperature peak just above the fire and at different distance from the fire.

Afterwards the unprotected steel structure subjected to this temperature field has been verified by using Eurocode 3 part 1.2.

Similar examples have been studied by our French partner the CTICM who has checked the fire stability of the air terminal 2F of the airport Charles de Gaule at Roissy (see NFSC 287) and by our Spanish partner LABEIN who has analysed the steel structure above an atrium of an office building in Madrid (Annex 5)

However, generally, the fire does not remain localised. For instance, in an office building, the fire spreads and finally engulfs the whole compartment.

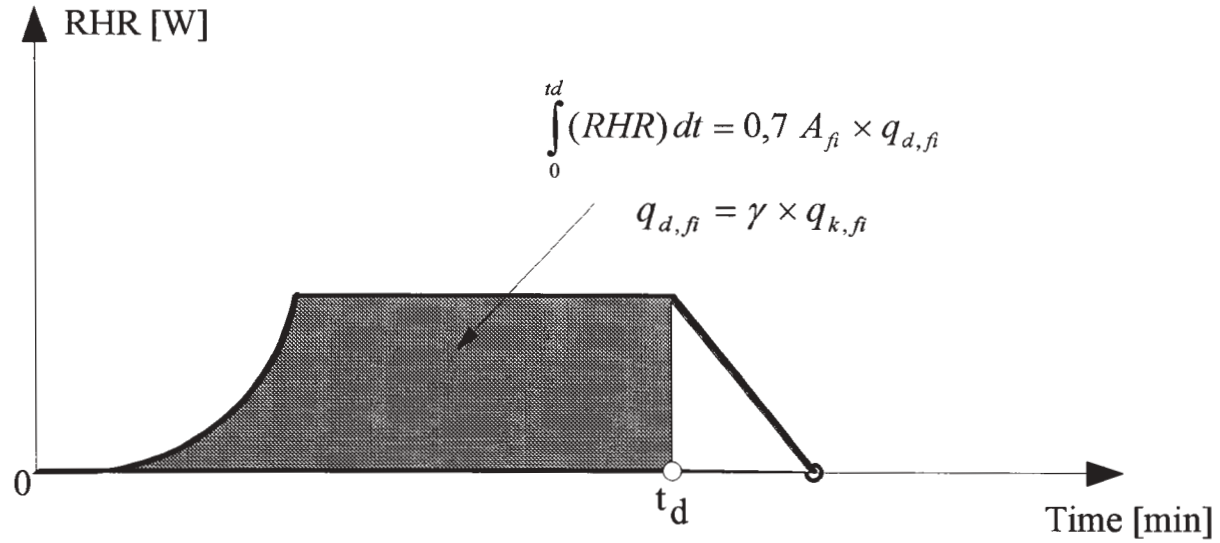


Figure 2.5 : Rate of Heat Release Curve – Stationary state and decay phase

After the growth phase, after that the whole compartment has been involved by the fire, the fire reaches a stationary state corresponding to the horizontal plateau of the RHR curve. The value of this plateau can be equal to the area of the compartment multiplied by the RHR_f corresponding to a fuel controlled fire or the value of this plateau is fixed by the oxygen content in the compartment. In this last case the fire is called ventilation controlled. Afterwards the power of the fire goes down. As noticed when analysing more than 80 tests made in laboratory which have been gathered during this research, the power of the fire starts to decrease when 70% of the fire load has been consumed. The fire load to be considered in the design is the characteristic fire load corresponding to 80% fractile multiplied by a weighing factor γ (see Figure 2.5).

This weighing factor γ has been established by extending to the calculation in case of fire the Annex A of Eurocode 1 which is the basis of the weighing factors on the static loads and of the safety factors on the materials properties. The theory leading to this weighing factor γ has been established in the scope of the WG5 (see chapter 7).

	Probability	
Occupancy	Fire Occurrence or Starting Fire p_{fi}^{st} [1/(m².year)]	Failure of Occupants & Standard Firemen in stopping the fire $p_{O\&SFB}^{fail}$ [-]
Industrial Building	10.10^{-6}	0,05 to 0,1
Office	10.10^{-6}	0,02 to 0,04
Dwellings	30.10^{-6}	0,0125 to 0,25

Table 2.2

This weighing factor γ is based on probabilities of fire start, fire spread and failure of active fire fighting measures (see Table 2.2). These probabilities have been deduced from fire statistics gathered in the department of BERNE in Switzerland (39.104 fires from 86 to 95), in Finland (2.109 fires in 95), in France (82.179 in 95) and from existing standards in Germany [7] and in UK [8].

This work has been performed by the Working Group 4 (WG4) under the leadership of Prof. M. Fontana (ETH) (see chapter 6).

This factor has been divided into subcoefficients γ_{q1}, γ_{q2}, γ_{ni} to take into account the compartment size, the building type and the different active fire fighting measures like sprinklers (see Figure 2.6).

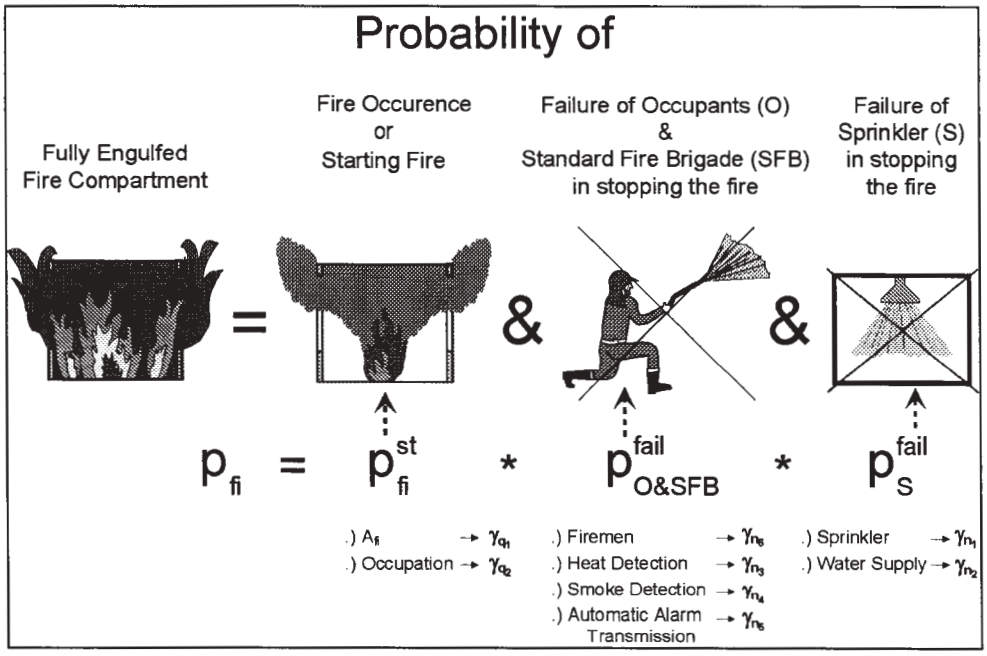


Figure 2.6 : Subcoefficients γ_{q1}, γ_{q2} and γ_{ni}

In order to perform a calculation you have to gather the data concerning the fire spread, the maximum rate of heat release per m^2, the characteristic fire load, the compartment size, the building use and the active fire fighting measures which enable to deduce the design fire load.

The WG3 leaded by Mr. Twilt (TNO) was in charged to define how to determine the fire scenarios, the fire compartment and all these starting data (see chapter 5). These characteristics enable to deduce the design curve of the Rate of Heat Release (see Figure 2.5).

The simulation tools to determine the gas temperature has been analysed and developed in the scope of the WG1 leaded by Dr Franssen (see chapter 3). For practical use, the WG1 proposes to uses a 2-Zone model at the beginning of the fire (see Figure 2.7) and to switch to a 1-Zone model if the 4 following conditions described on the Figure 2.8 are fulfilled.

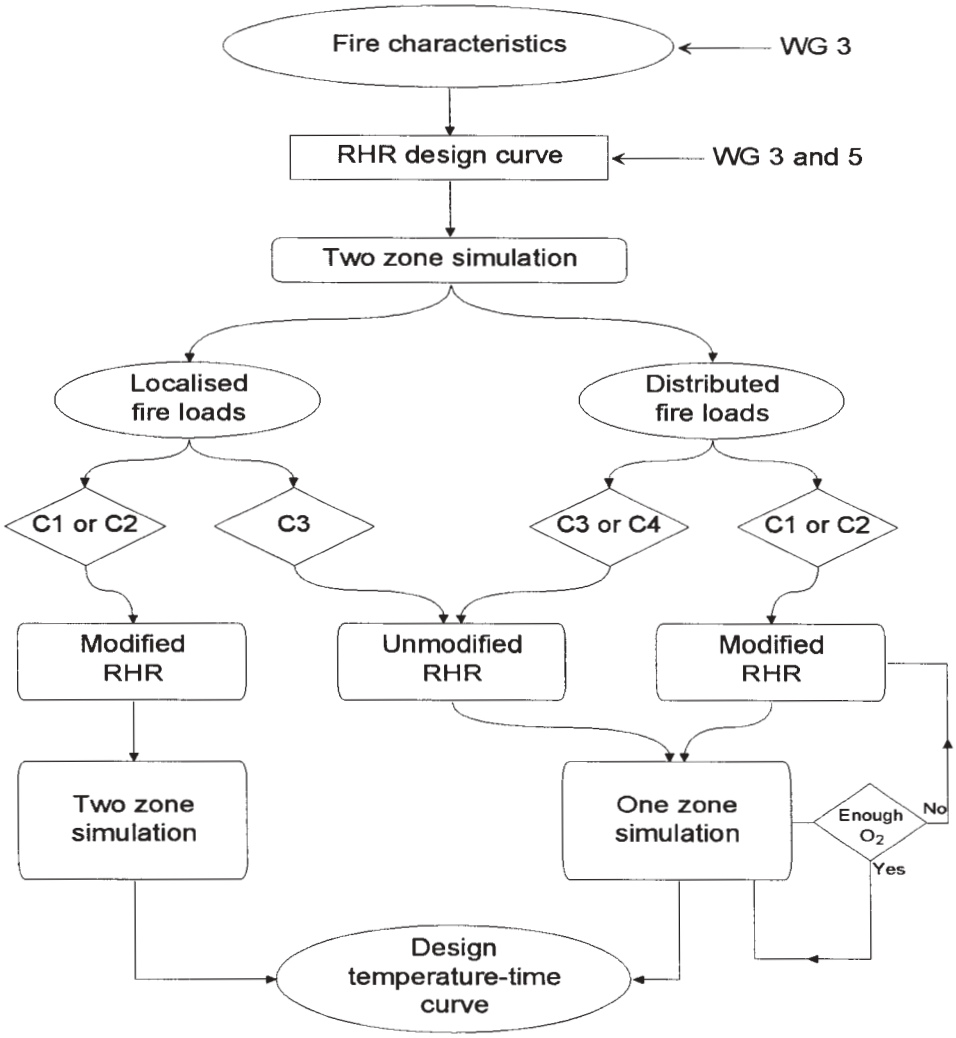


Figure 2.7 : Determination of the design temperature-time curve

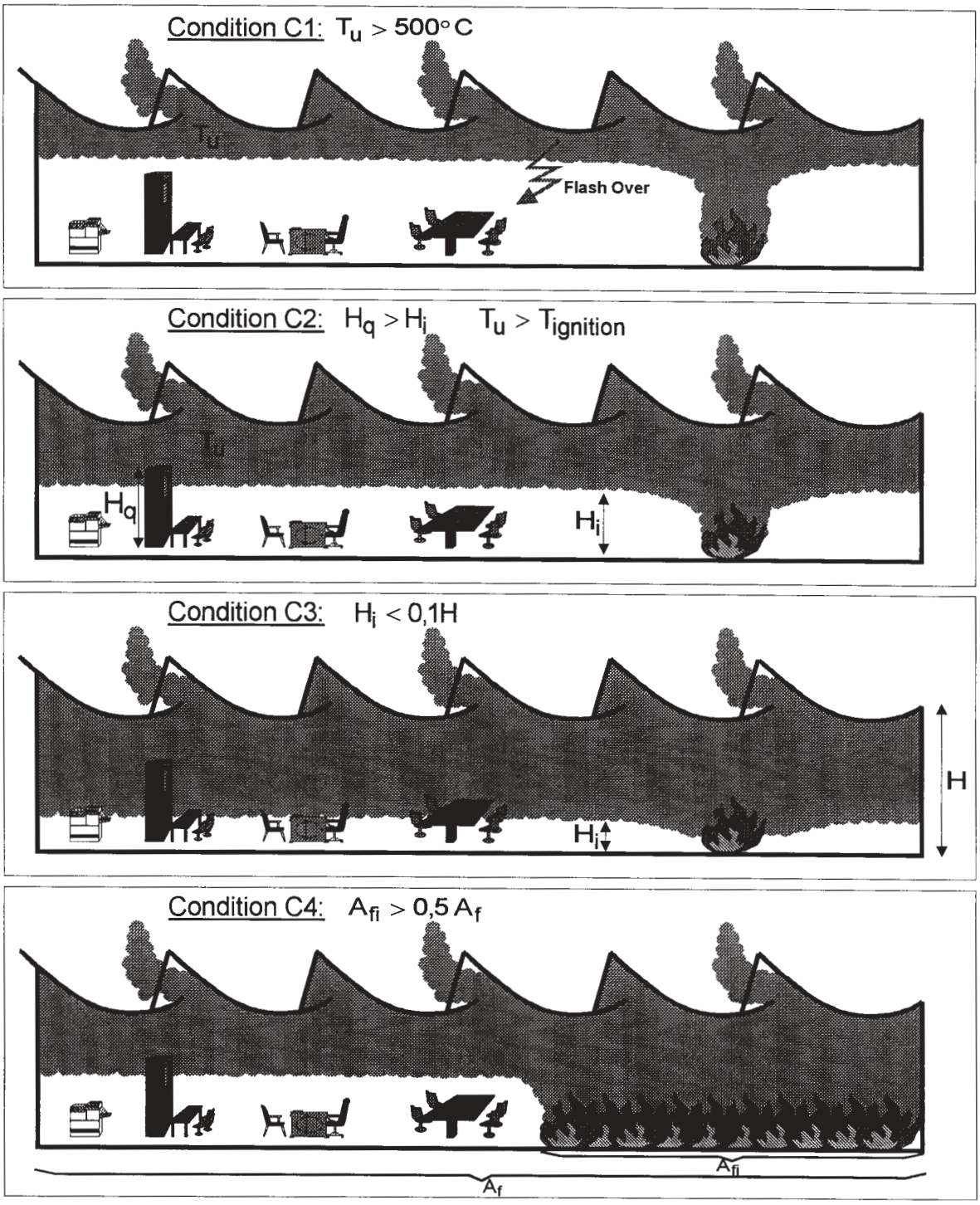

Condition C1: $T_u > 500°C$
T_u
Flash Over
Condition C2: $H_q > H_i$ $T_u > T_{ignition}$
T_u
H_q
H_i
Condition C3: $H_i < 0,1H$
H_i
H
Condition C4: $A_{fi} > 0,5\ A_f$
A_{fi}
A_f

Figure 2.8

In case of fully engulfed compartment, the program OZONE written by the University of Liège, provides the effective Rate of Heat Release which takes into account the oxygen content available in the compartment and which depends on the ventilation conditions of the compartment. On the example of the Figure 2.9, there is not enough oxygen to follow the design RHR curve. The program OZONE follows then a horizontal plateau until 70% of the fire load has been consumed. The descending branch is such that the areas beneath the two RHR curves are the same, because it corresponds to the design fire load.

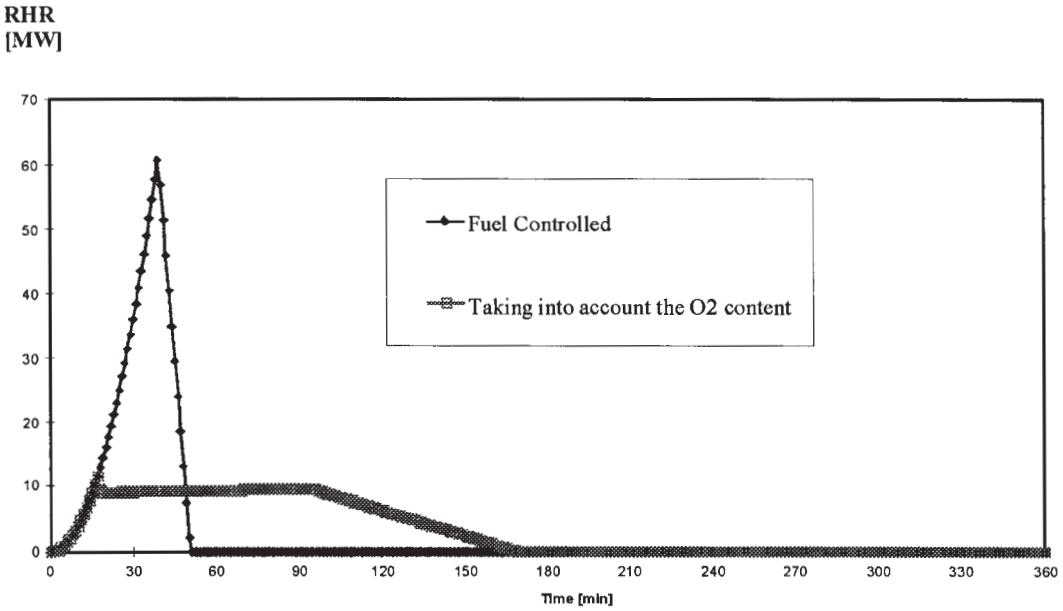


Figure 2.9 : Design and Effective RHR Curve for the Esch/Alzette Hospital (Scenario 4 : q_f= 242 MJ/m²)

The program also gives the temperature in the air and in the steel structure (see Figure 2.10). Knowing the steel temperature, the check of the structure can be performed either by using Eurocode 3 and 4 part 1.2 for single elements or by using well-known thermo-mechanical software to simulate the whole structure. (For instance SAFIR in University of Liège, SISMEF and LENAS in CTICM, DIANA in TNO, CEFICOSS in ARBED…)

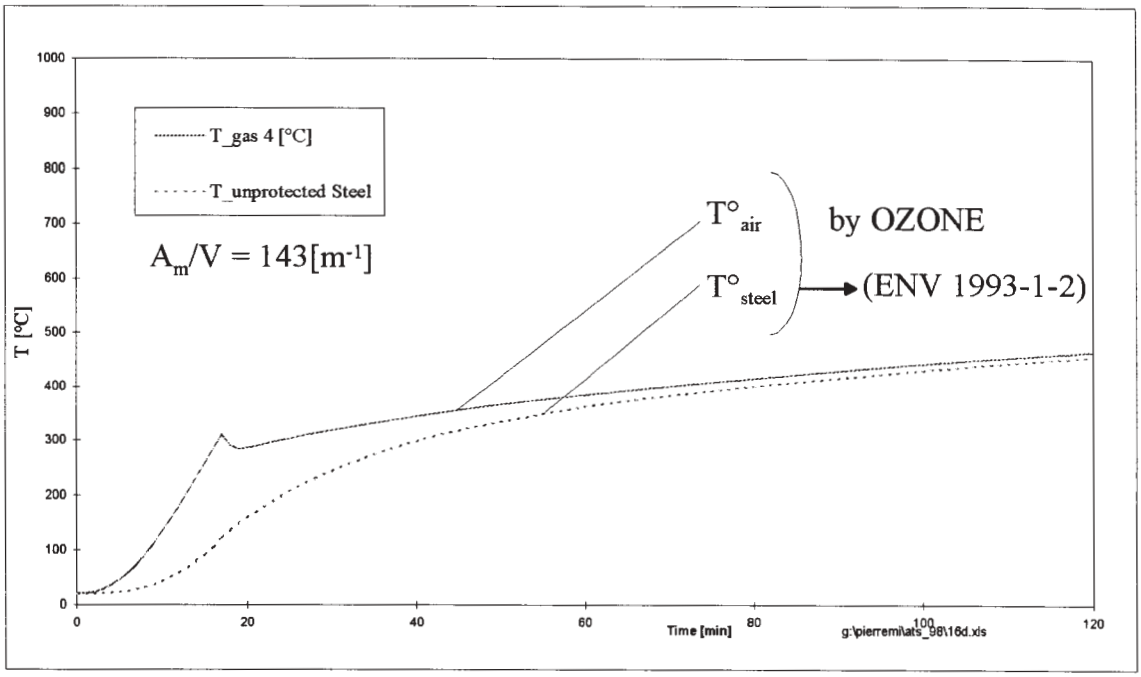


Figure 2.10 : Steel and Air Temperature Curves for the Esch/Alzette Hospital (Scenario 4 : q_f= 242 MJ/m²)

Similar types of study (see chapter 9) have been made by :

- the University of Liège for the Basket-Ball Hall of Pepinster (Belgium) [9]
- the CTICM for the "Law Courts" of Nantes (France)
- the "Structura Engineering" for the Museum and Exhibition Hall "Ancien Ducal Stable" in Urbino (Italy)
- the LABEIN for an Office Building in Madrid (Spain)
- the ETH of Zürich for the Office Building LANGENTHAL (Switzerland)
- the leader PA-RE for the complex "Geesseknäppchen" which is composed of a swimming pool, a sport hall, a forum and two schools

This new approach should lead to both financial benefits and better safety guidance. Hence, examples of its use should become more numerous. Less money will be wasted in attempts to guarantee resistance of structures subjected, for instance, to two hours of a wholly unrealistic ISO (or ASTM) fire. Instead, it will be evident that it is much better to identify the active fire fighting measures that provide protection for people, such as detection, alarms, automatic alarm transmission to fire-fighters, smoke exhaust systems, and sprinklers.

If the safety of people is ensured in an optimal way, the structure itself can also benefit from those measures that aim to save occupants. Hence, the further costs needed to guarantee its stability in case of fire are strongly reduced and, in some cases, even reduced to zero.

The new NFSC concept can be summarised in the following steps (see Figure 2.11):

I. Safety for Occupants

II. Safety of the Structure

II.1. Determination of the Requirement depending on the number of occupants, the mobility of occupants, the number of exit routes, the dimensions of the compartment, the height of the building...

II.2. Calculation of the fire resistance of the Structure.

1. To define a design fire (Rate of Heat Release, area, perimeter, position).
2. Does this fire remain localised or not ?

In case of localised fire	In case of fully engulfed compartment
3. Effect of the active measures - the area of the fire may be influenced by the active measure	3. Effect of the active measures -->the fire load is multiplied by some reduction factors γ_{ni}
4. /	4. Effect of the probability of fire occurrence -->the fire load is multiplied by the safety factors γ_{q1}, γ_{q2}.
5. Calculation of the gas temperature field Θ_g (x,y,z,t)	5. Calculation of the uniform natural fire curve (the gas temperature Θ_g (t))
6. Calculation of the temperature field in the structure Θ_a (x,y,z,t)	6. Calculation of the temperature in the structure (in case of unprotected steel structure, Θ_a (t))
7. Thermo-mechanical calculation of the structure	7. Thermo-mechanical calculation of the structure
This procedure is described in the Final Report of the ECSC research "Natural Fire in Large Compartment"[1].	The coefficients γ_{ni} et γ_{qi} enable us to quantify the risk of fire and the influence of the active fire fighting measures, to deduce a design fire load which will be used to calculate a fire curve and a resistance time $t_{fi,d}^{nat}$. This resistance time will have to be compared with the required time $t_{fi,req}$, which depends on the evacuation time and the consequences of the failure of the structure. The determination of $t_{fi,req}$ is out the scope of this research but a proposal to obtain $t_{fi,req}$ has been described in the semestrial report n°3 [2].

The works have been shared into 5 Working Groups (see Figures 2.12 and 2.13):

- the Working Group 1 (ULg, CREA, CTICM, LABEIN, TNO, PA-RE) entitled "Natural Fire Models" is dealing with points II.2.2, II.2.5 and II.2.6,

- the Working Group 3 (TNO, CTICM, PA-RE) entitled "Fire Characteristics for use in a natural fire design of building structures" with the points II.2.1 and II.2.2,

- the Working Group 4 entitled "Statistics" (PA-RE, SAES, ECCS, Ubo, CTICM, BCSA) with the point II.2.3.

- the Working Group 5 entitled "Methodology to deduce from the probability data the design natural fire curve" (PA-RE, SAES, ECCS, Ubo, CTICM, BCSA) with the points II.2.3 and II.2.4.

- the Working Group 2 (SAES, ECCS, Ubo, LABEIN, PA-RE) entitled "Equivalent ISO-Time Methods" to analyse the methods existing at the beginning of the research and considering the ventilation conditions and the fire loads, but referring nevertheless to the ISO-Curve (see Figure 2.13). It has to be pointed out the "Equivalent Time Methods" do not belong to the Natural Fire Safety Concept developed and finally proposed here (see Figure 2.12).

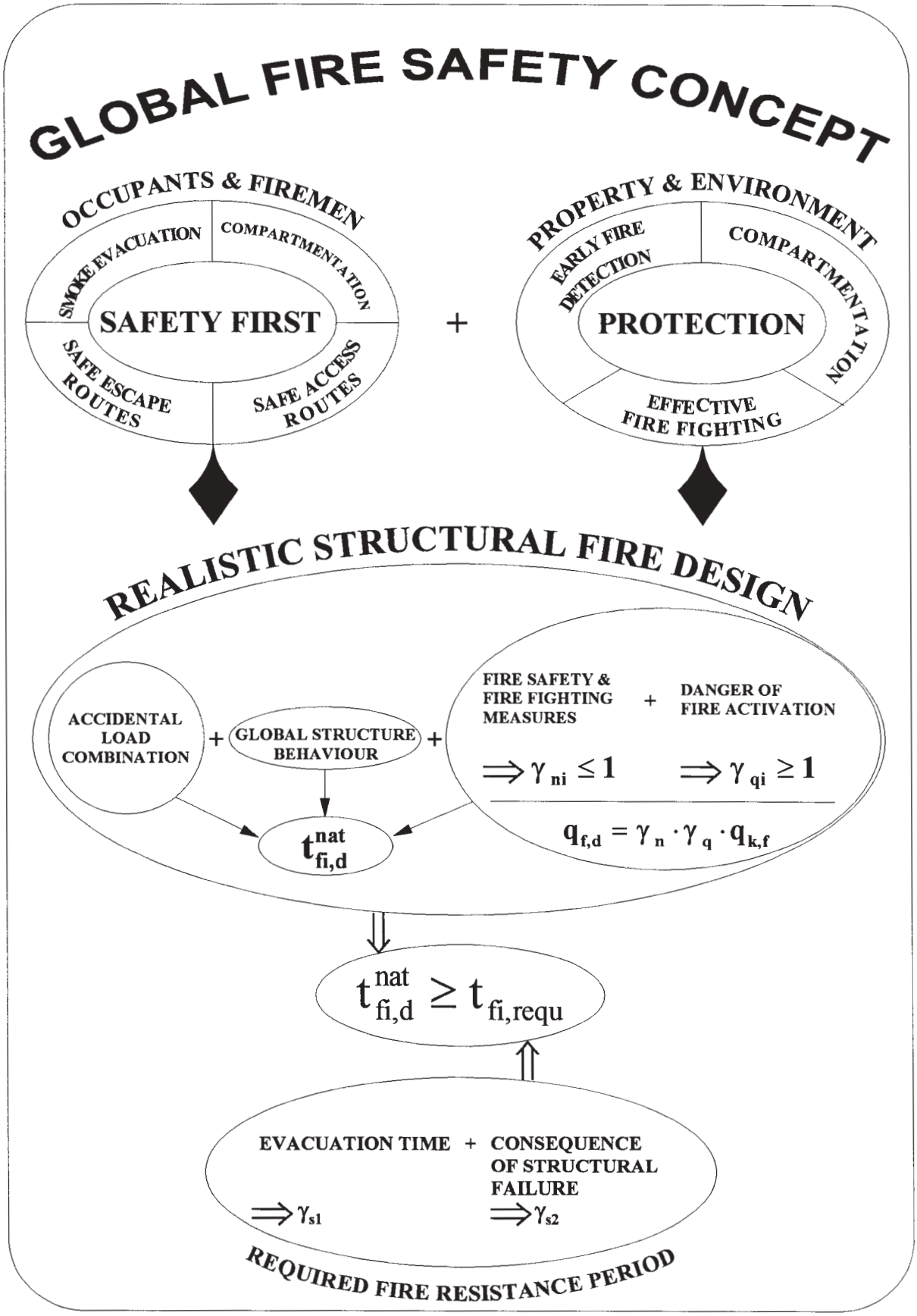

GLOBAL FIRE SAFETY CONCEPT
OCCUPANTS & FIREMEN
SMOKE EVACUATION
COMPARTMENTATION
SAFETY FIRST
SAFE ESCAPE ROUTES
SAFE ACCESS ROUTES
+
PROPERTY & ENVIRONMENT
EARLY FIRE DETECTION
COMPARTMENTATION
PROTECTION
EFFECTIVE FIRE FIGHTING
REALISTIC STRUCTURAL FIRE DESIGN
ACCIDENTAL LOAD COMBINATION
+
GLOBAL STRUCTURE BEHAVIOUR
+
FIRE SAFETY & FIRE FIGHTING MEASURES
+
DANGER OF FIRE ACTIVATION
$\Rightarrow \gamma_{ni} \leq 1$
$\Rightarrow \gamma_{qi} \geq 1$
$t^{nat}_{fi,d}$
$q_{f,d} = \gamma_n \cdot \gamma_q \cdot q_{k,f}$
$t^{nat}_{fi,d} \geq t_{fi,requ}$
EVACUATION TIME
+
CONSEQUENCE OF STRUCTURAL FAILURE
$\Rightarrow \gamma_{s1}$
$\Rightarrow \gamma_{s2}$
REQUIRED FIRE RESISTANCE PERIOD

Figure 2.11

Natural Fire Safety Concept
Static Loads
Wind
Self Weight
Imposed Load
Snow
.....
Fire Characteristics
WG3
Fire Load
Ventilation Conditions
Geometry
Thermal Characteristics of Enclosure
Probabilistic Aspect
WG4
Active Fire Measures
Risk of Fire Activation
Evacuation Time
Consequence of Structural Failure
WG1
WG5
Natural Fire Curve
θ
t
WG1
Natural Fire Curve
Design Natural Fire Curve
θ
t
Realistic Load Combination (Accidental)
GLOBAL BEHAVIOUR OF THE STRUCTURE
$t_{fi,d}^{nat} \geqslant t_{fi,requ}$

Figure 2.12

Natural Fire Safety Concept based on the Equivalent Time
Static Loads
Wind
Self Weight
Imposed Load
Snow
.....
Probabilistic Aspect
Active Fire Measures
Consequence of Structural Failure
Fire Characteristics
Fire Load
Ventilation Conditions
Geometry
Thermal Characteristics of Enclosure
Realistic Load Combination (Accidental)
ISO Curve
θ
1006
842
30'
90'
t
Equivalent Time
t_e
WG2
GLOBAL BEHAVIOUR OF THE STRUCTURE
$t_{fi,d}^{ISO} \geqslant t_{fi,requ}$

Figure 2.13

3 WORKING GROUP 1 "NATURAL FIRE MODELS"

3.1 INTRODUCTION

The most important results obtained by Working Group 1 during the course of the research Natural Fire Safety Concept are presented in the final report produced by this Working Group (see Document Part 2 defined on the cover page).

The first part of this report, comprising Chapters 1 to 4, contains general information related to different fire models that can be found in the literature. This information has been sorted and organised in a systematic way in such a way to form a clear introduction to the topic of fire modelling. In this sense, it does not contain new pieces of scientific material. Among various models, the one zone models, the two zone models and the computational fluid dynamic models are described more specifically.

The second part of the WG1 report contains the new material established or collected within the course of this research. A data base of well documented fire tests has been established to be used in comparisons with various models, a new one zone model has been written and validated, a new proposal based on the tests of the data base has been made for a parametric fire and, finally, some clear guide lines have been given for the choice of a fire model.

Additional information is given in the annexes on particular points examined within this research project, namely the connection between parametric temperature-time curves and equivalent time of fire exposure given in Eurocode 1 and a comparison between equivalent times from Eurocode 1 and experimental tests. This summary is organised according to the structure of the Working Group 1 report.

3.2 GAS TEMPERATURE IN A FIRE COMPARTMENT - SUMMARY OF THE DIFFERENT CALCULATION METHODS

Some elements of the physic of a fire are quoted. A fire generally comprises different phases in its duration: ignition, growth, flashover, phase of full development and cooling phase. It is also important to distinguish whether there is at any time enough oxygen to burn all the fuel available, in which case the fire is said **fuel controlled,** or whether there is not enough oxygen entering the compartment to burn all the fuel available, in which case the fire is said **ventilation controlled**.

The nominal fire curves – as the ISO 834 curve – are not real natural fire models. They consist of arbitrary time temperature relationships. For the nominal fires, the temperature is continuously increasing in the compartment.

The parametric fires are also time temperature curves, but theses curves depend, in each particular case, of the 3 scalar parameters representing the main physical parameters that influence a real fire : the fire load, the openings and the nature of the walls of the enclosure. They are normally made of a heating phase followed by a cooling down phase.

The one zone models are numerical programs that integrate with respect to time the mass and the energy balance equations describing the situation. They are based on a more detailed description of the geometry of the compartment – for instance, each opening is modelled individually – and of the evolution of the fire – not only the amount of fuel is taken into account, but also its combustion rate. They are valid in the post flashover phase, i.e. for fully developed fires. The main result is also the evolution of the temperature with time.

In all the models described up to this point, the temperature is assumed to be uniform in the compartment at any time. In the **two zone models**, the compartment is divided vertical in two different zones : the upper zone containing the hot combustion products and the lower zone in which the temperature remains rather low. These models are valid for localized fires. The main results are the evolution of the temperature in the upper zone and of the thickness of the clear lower zone.

The **Computational Fluid Dynamic (CFD) models** are complex computer codes which provide the evolution of several variables in a very great number of positions in the compartment. They require extremely powerful computers and can be operated only by very experienced user. The utilisation of the results for a structural analysis is by far not obvious.

Two examples have been run with existing tools and this showed :

- The results obtained with different zone models can be very different.
- In zone models, wall models are essential.
- The link between the energy balance and the mass balance seems to be weak.

This exercise was one of the motivations for the group to develop the new one zone model ***OZone***.

3.3 ONE ZONE MODELS

The low computing time and the realist hypothesis of uniform temperature in case of fully developed fire makes the one zone models a helpful tool to estimate the temperature in a compartment in post-flashover condition. This is why one Chapter is dedicated to more detailed information about these models.

A section is dedicated to some fundamentals: first the basic equations, then the sub-models for the energy released by the fire, for the gas flow through the openings and for the heat exchange to the walls. Another section is dedicated to the input data.

3.4 TWO ZONES MODELS

Some fundamentals are also given here, including theoretical basic formulations. A new feature, compared to the one zone models, is the model describing the amount of air entrained by the plume of the fire from the lower zone into the upper zone. A review has been made of 2 existing two zone models, namely C.T.T. from ULg and CFAST from NIST.

3.5 COMPUTATIONAL FIELD MODELS

Some fundamentals are given concerning the pre-processor, the solver and the postprocessor. The input data and the application range are also discussed.

3.6 DATABASE OF THE NATURAL FIRE TESTS

In order to be able to validate the air temperature field calculation methods in fully engulfed compartments, a database has been made from the collection of natural fire tests.

As a whole, it contains 105 tests made in 4 countries. Some of these can not be used in our comparisons either because they concern very large compartments where the temperature was by far not uniform or because the final report of the test has not yet been published. Thus, 69 tests remain for use in comparison exercises.

Each test has been summarized on an EXCEL sheet containing administrative information, the geometry of the compartment, the description of the walls, information on the fire (fire load and heat release rate when available). The results are made of the evolution of the minimum, maximum and average temperature recorded in the compartment.

The compartments have a maximum volume of 35 m^3, and a maximum height of 3,13 meters. The openings are in one vertical wall. In most of the tests, the fire load is between 15 and 60 kg of wood / m^2.

3.7 THE ONE ZONE MODEL *OZONE* - DESCRIPTION AND VALIDATION BASED ON 54 EXPERIMENTAL FIRE TESTS

Some of the main features of ***OZone*** are presented here.

- The variation of C_p of the air with temperature is taken into account.
- The time integration of the differential equations is made by the specialised library solver DEBDF.
- The walls are discretised by the finite element technique. The equations of conduction in the walls are transformed into ordinary differential equations in such a way that they can be integrated by the solver simultaneously with the equations describing the evolution in the compartment. This procedure guarantees that the energy balance is respected at the interface between the compartment and the wall.
- Bernoulli's law is used for the mass exchange through the openings. Radiation through the openings is taken into account where air is entering the compartment.
- The rate of heat release and of mass burning (pyrolisis rate) during the fire can be introduced by the user.

- If no combustion model is activated (CM0), these data will be strictly respected by the program. This procedure has to be used in order to model an experimental test in which these quantities have been measures.
- Combustion model 1 (CM1) respects the pyrolisis rate but will reduce the energy release if not enough oxygen is flowing in the compartment. This is equivalent to external flaming and will not extend the duration of the fire.
- With combustion model 2 (CM2), the pyrolisis rate and, consequently, the heat release rate are both modified in case of air control, tending to increase the duration of the fire. In this case, a linear cooling down phase starts when 70% of the fuel present in the compartment has been burnt. This safe approach has to be used in case of practical design.

The different combustion models are presented schematically in Figure 3.1.

- A user friendly pre-processor has recently been created. This allows an easy introduction of the data via a graphic user interface.

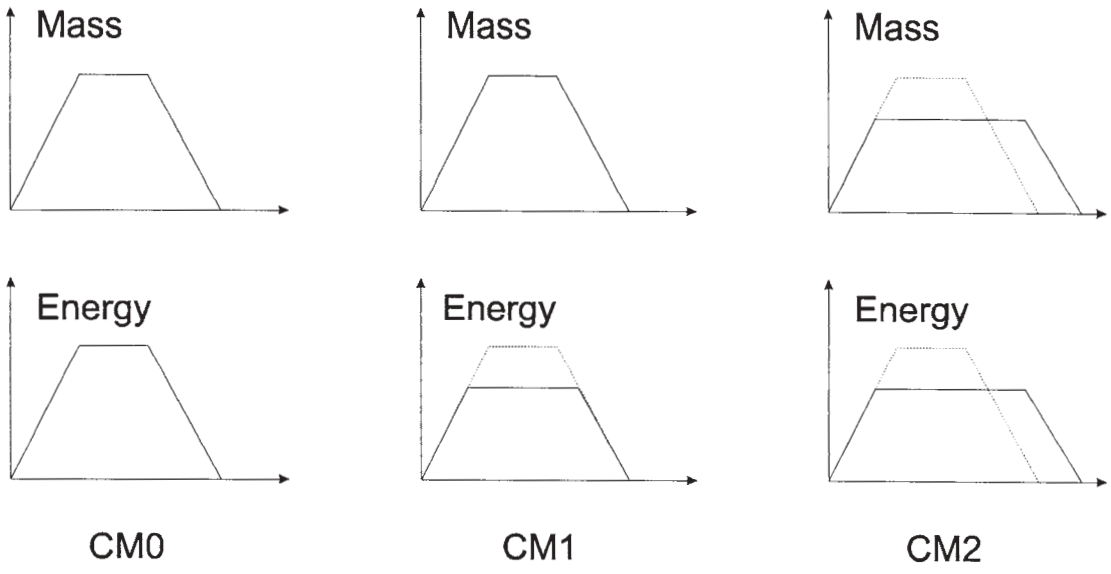


Figure 3.1 : combustion models

OZone has first been validated for an academic example by comparison with the code NAT written by C.S.T.B and used here by C.T.I.C.M. The results fit perfectly well, for the temperature as well as for the different terms of the mass balance.

The comparison has also been made with 54 tests of the data base. Figure 3.2 shows the comparison for the maximum temperature in the air. The coefficient of correlation (CR) is equal to 0,96. The comparison has also been made on the maximum temperature in an unprotected steel section (CR = 0,96) and in a thermally protected steel section (CR = 0,96)

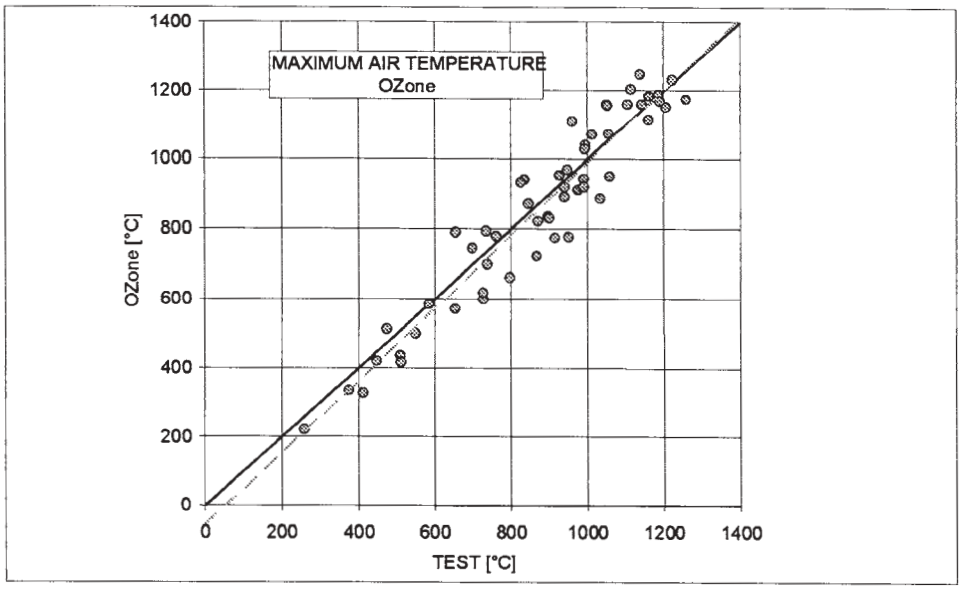


Figure 3.2 : comparison *OZone* – tests

3.8 A COMPARISON BETWEEN THE PARAMETRIC FIRE OF EUROCODE 1 AND EXPERIMENTAL TESTS

The basic equations and the field of application of the parametric fire proposed in Eurocode 1 are first presented.

The comparison is then made between this proposal and 48 tests of the database.

Figure 3.3 shows the comparison for the maximum temperature in the air. The coefficient of correlation (CR) is equal to 0,25, which means that the correlation is very weak. The correlation is somewhat better for the maximum temperature in an unprotected steel section (CR = 0,66) and in a protected steel section (CR = 0,80).

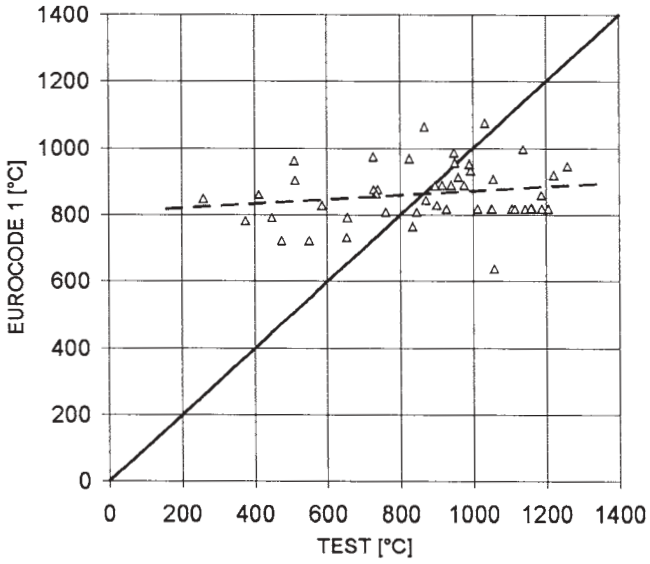


Figure 3.3 : comparison EC1 - tests

Some proposals are made as how the agreement can be improved. They are:

A more correct way to calculate the thermal effusivity (*b* factor) in walls made of layers of different materials.

The introduction of a minimum duration of the fire, taking into account a fuel controlled fire when the fire load is low and the openings are large.

A correction factor that takes into account the large mass flow in case of fuel controlled fires.

With these improvements, the correlation factor CR becomes equal to 0,84 (maximum temperature in the air), 0,77 (maximum temperature in an unprotected section) and 0,80 (maximum temperature in a protected section). Figure 3.4 shows the comparison for the temperature in the air.

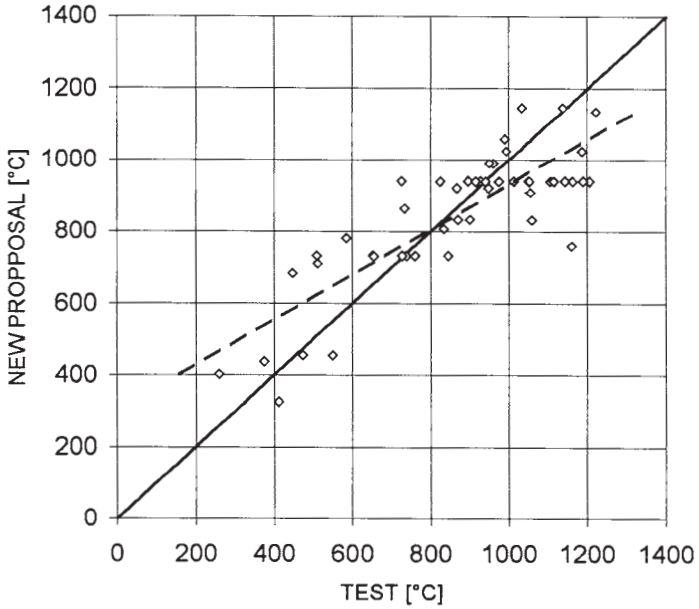


Figure 3.4 : comparison NFSC proposal - tests

3.9 CHOICE OF THE NATURAL FIRE MODEL : PRACTICAL GUIDELINES

As every fire normally starts as a local source, the two zone model normally prevails in the early stage. Four conditions are listed which can make the two zone model non valid and which oblige to switch from this time to a one zone model.

Depending on whether the fire load is uniformly distributed or is localized in the compartment, different situations can occur with respect to the occurrence of a flash over. They are described and analysed separately in this Chapter and recommendations are given how to relate the results from the two different models that have been applied successively.

4 WORKING GROUP 2 "EQUIVALENT ISO-TIME METHODS"

It has to be pointed out that the WG2 report is in fact provided because the work has been done in the scope of the research but the "Equivalent Time Methods" do not belong to the Natural Fire Safety Method developed and finally proposed.

These "Equivalent Time Methods" have been analysed at the beginning of the research because, at that time, it was the only existing methods considering the ventilation conditions and the fire loads. However the weak point is that these methods refer to the ISO-Curve and do not depend on the structure type (protected steel, unprotected steel, reinforced concrete).

Despite the numerous numbers of available methods, only two different procedures exist in fact:

- New-Zealand method (it is an updated Petterson's version of the method) [10]
- Annexe E of ENV 1991-2-2 [3] (it is in fact the DIN 18230 – version 94 [12])

The comparison between the results of the last method and the similar results deduced from the test database (see WG1 report) attest that the Annex E of EC1 part 2.2 gives very good results in case of protected steel structures (see Figure 4.1). For unprotected steel structures the method is less efficient but seems to give reasonable results (see Figure 4.2). These conclusions are of course limited to the conditions covered by the database and to the steel profile used in the comparison.

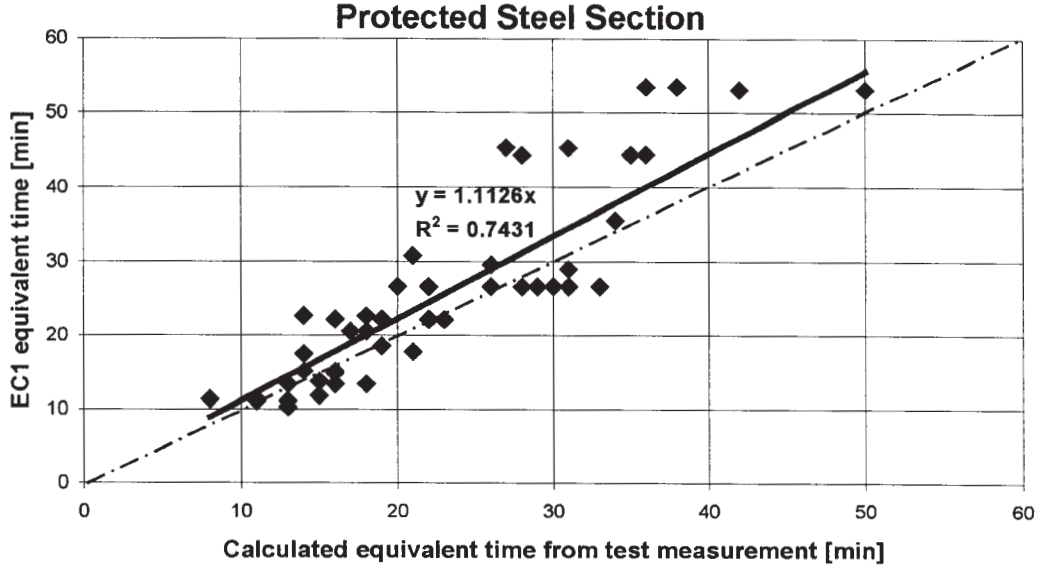


Figure 4.1: Comparison between "equivalent times" according to EC1 and deduced from the tests database for PROTECTED steel profile

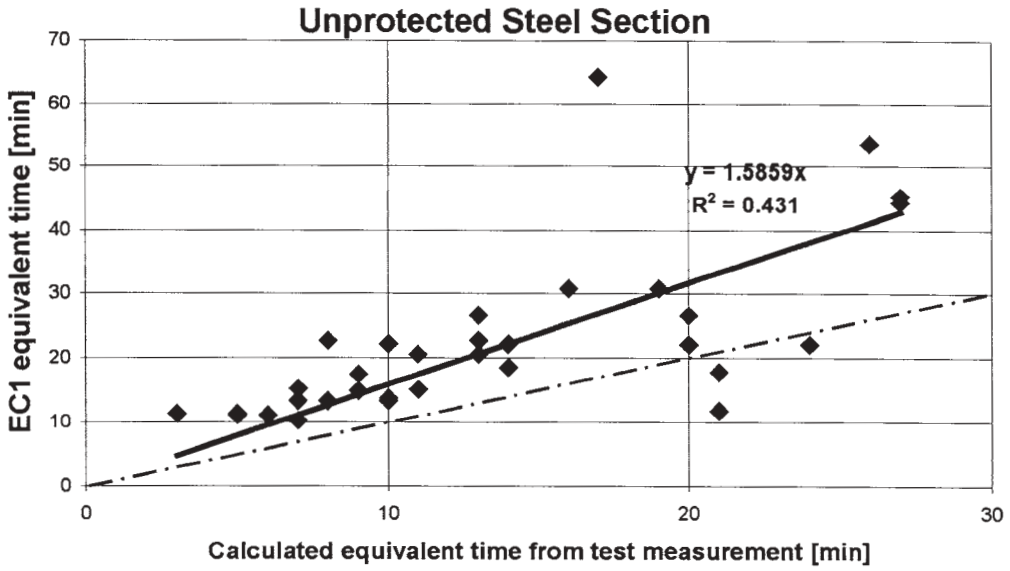


Figure 4.2: Comparison between "equivalent times" according to EC1 and deduced from the tests database for UNPROTECTED steel profile

The Equivalent Time Method defined in ENV 1991-2-2 is a simplified method that may be used in a first approach. However it has to be kept in mind that, mainly for the unprotected steel structure, the results have to be checked by the full NFSC method described in the other Chapters of this report.

Moreover the equivalent time based on a unique temperature equivalence is not valid anymore for composite construction.

5 WORKING GROUP 3 "FIRE CHARACTERISTICS FOR USE IN A NATURAL FIRE DESIGN OF BUILDING STRUCTURES"

5.1 INTRODUCTION

In the "Natural Fire Safety" approach the fire safety design is based on physically determined thermal actions. In contrast with the conventional design, parameters like the amount of fire load, the rate of heat release and the amount of ventilation play an important role in the natural fire design. The specification of appropriate design fire scenarios (i.e. the course of a fire with respect to time and space) is a crucial aspect of fire safety design. The assumptions made with regard to these factors have major influence on the conditions in the compartment and have significant impact on the fire design.

The design fire scenarios used for the analysis/development of a building fire have to be deduced from all the possible fire scenarios. In most buildings the number of possible fire scenarios is infinite and need to be reduced to enable analysis and calculation. If the design fire scenarios are chosen, a number of fire models is available to calculate the thermal actions.

The work of Working Group 3 "Fire Characteristics" is to supply the input data and to supply ready-to use guidance on these data for the Natural Fire Design. The results of the work are in the WG3 report. This Chapter 5 gives only the most important operational information. For details refer to the full WG3 report.

The following topics are given in this Chapter 5:

- Introduction
- Enclosure
- Fire load density
- Fire scenario/Rate of heat release
- Thermal properties of boundaries
- Heat transfer to structural elements

The starting point for calculating thermal actions (modelling) is the fire in the enclosure where the fire starts. The fire (scenario) depends on the ignition source, the amount and type of fuel, the size of the enclosure, the amount of ventilation, the growth rate, the rate of heat release etc. Starting with a small growing fire, growing to flashover and dying after the available fire load is consumed. Sophisticated computer models can take all these stages of the fire into account. The necessary input data is given in the next paragraphs.

5.2 THE ENCLOSURE

For the spread of fire in a building it is important to know the behaviour under natural fire conditions of the boundary elements of the enclosure where the fire started (walls, doors, windows). The development of the conditions in a building depends on all these factors. In modelling a fire using computer codes it is important to make assumptions about the behaviour of separating elements/boundaries. The assessment of the actual behaviour under natural fire conditions is a very complicated task. Looking at the results of standard fire resistance testing, it is clear that the behaviour of complicated elements cannot –at this moment- be predicted theoretically. Only for simple well described elements a theoretical (calculation) approach is possible, for all other elements a simple approach should be used.
In the next paragraph this approach is given.

5.2.1 BOUNDARY ELEMENTS

The behaviour of boundary elements can be assessed by:

- Ad-hoc tests
  The element can be exposed to a temperature-time curve in a furnace, as calculated with fire models based on the worst-case fire scenarios. Problems are:
  -the worst case scenario is -a priori- not known;
  -the number of fire tests needed is very large.
- Expert judgement
  This approach makes use of the available test-data of ISO-resistance tests on separating elements. In combination with calculation procedures, the behaviour under natural fire conditions can be assessed for a limited number of simple elements (e.g. monolith walls). For more complex wall constructions this approach is not feasible.
- Direct use of ISO-requirements
  National rules require a certain ISO-fire resistance of walls and floors, depending on their use and geometry. Direct use of ISO-requirements is based on the following assumption: a fire will not grow beyond the fire compartment, if the boundaries are fulfilling these national rules.
  If the fire starts in an enclosure without ISO-fire rating boundaries within a fire compartment, the fire will stay in the enclosure for 15 minutes and after that the fire compartment is progressively involved. This is a rough but easy approach.

Conclusion:
The first two options can be used for a limited number of separating elements, and will lead to high costs. In practise, often the 3rd option has to be used.

5.2.2 OPENINGS (WINDOWS, GLAZING, DOORS, EXTRACTION VENTILATORS)

Openings in an enclosure can consist of windows, doors and roof vents. The severity of the fire in an enclosure depends on the amount of openings in the enclosure. The following rules are proposed:

- Doors are assumed to be closed if the enclosure has other openings.
- Doors are assumed to be opened if the enclosure has no other openings.
- Glazing without ISO fire rating is broken from the start of the fire. If the size of the window/glazing in a certain wall is higher than 50% of the total surface of that wall surface, only 50% of that wall surface is assumed to be broken; (upper part of the glazing/wall). This assumption is based on the notion that normal glass will break at relative low temperatures.
- For glazing with an ISO fire rating, the same approach as with separating elements can be used (adhoc, expert or direct use ISO-requirements).
- Simple models can use the so-called opening factor to model the openings in an enclosure. More complex models can use a flow calculation based on the actual flow through an opening.
- The opening factor can be calculated for enclosures with one vertical opening, with multiple vertical openings and with a combination of horizontal and vertical openings. Complex models (solving mass/heat balance equations) are also available (e.g. OZONE).

The heat in an enclosure can be lost from the enclosure by radiation and by convection. The convection part can be calculated with a simple model (using the opening factor) or complex models (solving mass/heat balance equations).

The heat loss to the walls of the enclosure may be neglected, but this will lead to conservative outcomes. Both a simple thermal-inertia approach and more sophisticated models are readily available to quantify the effect.

5.3 FIRE LOAD DENSITY

The fire load Q in a fire compartment is defined by the total energy liable to be released in case of fire. Part of the total energy will be used to heat the compartment (walls and air), the rest of the energy will be released through openings.
Building components such as wall and ceiling linings, and building contents, such as furniture, constitute the fire load. Divided by the floor area, the fire load Q gives the fire load density q_f.
In EC 1, the characteristic fire load density is defined by the following equation:

$$q_f = \frac{1}{A_f} \sum_i \left(\psi_i \cdot m_i \cdot H_{ui} \cdot M_i \right)$$

where:

M_i = the mass of the material i (kg)
H_{ui} = the net calorific value of the material i (MJ/kg) (see Table 4.2 of the WG3 report)
m_i = the factor describing the combustion behaviour of the material i
Ψ_i = the factor of assessing protected fire load of the material i
A_f = the floor area of the fire compartment

$H_{ui}.M_i$ represents the total amount of energy contained in material i and released assuming a complete combustion. The 'm' factor is a non-dimensional factor between 0 and 1, representing the combustion efficiency: m = 1 corresponds to complete combustion and m = 0 to the case of materials that do not contribute to the fire at all. A value of m = 0,8 is suggested for standard materials. For the wood, a value of 17,5 MJ/kg is suggested for H_u leading to 14 MJ/kg for (mH_u).

Estimating the fire load density can be done by summing all the fire loads present in a building. This is a deterministic approach.
Some information is available on the fire load density for specific building types like offices, schools etc. This statistical approach is only valid for building types where similar amounts of fire load can be expected. In those cases the fire load density can be given as a statistical distribution with a mean value and a standard deviation.
In the next table for a number of building types these values are given. The values are based on the Gumbel type I distribution. The values (for 80, 90 and 95% fractiles) are calculated using this distribution, assuming a variation coefficient of 0,3.
(Refer to the full WG3 report for details)

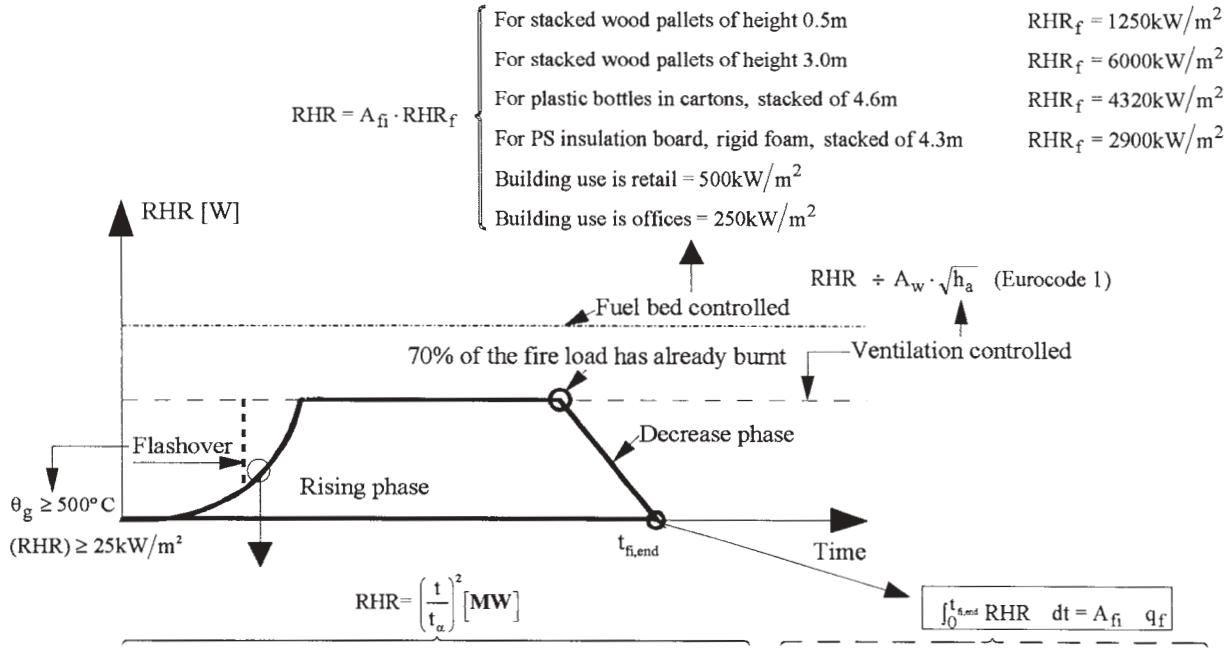
	Stand. Deviation	Mean	80% fractile	90 % fractile	95 % fractile
Dwelling	234	780	948	1085	1217
Hospital	69	230	280	320	359
Hotel (room)	93	310	377	431	484
Library	450	1500	1824	2087	2340
Office (standard)	126	420	511	584	655
School	85,5	285	347	397	445
Shopping centre	180	600	730	835	936
Theatre (cinema)	90	300	365	417	468
Transport (public space)	30	100	122	139	156

Table 5.1: Data on fire load density for different buildings and functions (variable load only Gumbel type I distribution assumed).

5.4 RATE OF HEAT RELEASE

The actual conditions in a fire compartment are based on the rate of heat release of the fire. After a growing phase, the fire will become steady-state either by limitation of the oxygen supply through openings, or by the limited amount/surface of the fuel.
The actual fire scenario will depend on a lot of factors, like the ignition source, the location of the fire, the actual position of the fire load etc.
For modelling a fire, this information is not at hand in most of the cases. Therefore a 'design' fire has been developed. This fire consists of a growing phase, a steady state phase and a decay phase. Depending on the actual parameters (slow growing fire, large openings, small amount of fire load) the design-RHR curve can be calculated.

In the following Figure 5.1 the proposal for the RHR curve for the NFSC project is given. The curve includes the growing phase, steady state and the decay phase. Linear decay phase starts when 70% of the fire load is burnt.
(Refer to the full WG3 report for details)



Fire growth rate	Typical equivalent materials	t_σ: Time [s] for RHR = 1 MW	Occupancy
Slow	no uniform fire load	600	Picture gallery
Medium	Cotton/polyester sprung mattress	300	Dwelling Hotel reception Office Hotel bedroom
Fast	Full mail bags, plastic foam, stacked timber pallets	150	Shop
Ultra-fast	Methyl alcohol pool fire, faster burning upholstered furniture	75	Chemical Plant

OCCUPANCY	Fire load (80 % fractile) $q_{k,f}$ [MJ/m²]
Dwelling	948
Hospital	280
Hotel (room)	377
Library	1824
Office (standard)	511
School	347
Shopping centre	730
Theatre (cinema)	365
Transport (public space)	122

Figure 5.1: Summary of the proposal for the RHR curve for the NFSC project, including the growing phase, the steady state and the decay phase.

5.5 HEAT LOSS TO BOUNDARIES

The heat loss from the compartment is an important factor for the temperature development in the fire compartment. Heat losses to the compartment boundaries occur by convection and radiation. A substantial amount of heat can also be removed from the compartment by the flow of hot gases through openings.

It has been known for a long time that the heat losses to the compartment boundaries can play a decisive role in determining whether a given fire will develop to flashover or not. This is why even the simpler approaches to fire modelling take this aspect into account. In the full WG3 report a detailed discussion is given on the subject.

Thermal inertia: b-factor
The most popular way to take into account the heat loss to boundaries is through the concept of the "thermal inertia" by using the b-factor of the wall material. This b-factor is defined for a homogeneous wall construction by:

It can be shown that under certain conditions (i.e. "thermally thick" wall, constant surface temperature) the heat flux into the wall depends on the b-factor only.

The heat loss to boundaries (walls, ceiling and floor) of a fire compartment plays an important role in the temperature development in the compartment. The following approach is suggested for the modelling of thermal inertia of the boundaries.

For the modelling of heat losses to the homogenous walls, the use of the b-factor

$$b = \sqrt{\lambda \cdot \rho \cdot c_p} \qquad (5\text{-}1)$$

where:

λ = heat conductivity in W/mK
ρ = mass density in kg/m^3
c = heat capacity in J/kgK

is suggested for models that can not calculate the actual loss of heat.

For sandwich constructions, - consisting of a number of materials with different b-factors - for the value of the effective b-factor of the construction another approach is suggested.

For these materials the smallest b factor of the individual materials should be taken. For specific types of material combinations the full report of WG1 gives a rule that can be used.

For the NFSC we suggest to neglect the effect of the water content; the thermal inertia (b-factor) for the wall should be calculated using the value for λ, ρ and c_p at ambient conditions (20 °C, 10% vol). See the full WG3 report for details.

Material	Lambda [W/mK]	Rho [kg/m^3]	C_p [J/kg.K]	b-factor [J/m^2.s$^{1/2}$.K]
Normal weight concrete	2,0	2300,0	900,0	2034,0
Light weight concrete	1,0	1500,0	840,0	1122,0
Middle weight concrete	1,0	2000,0	840,0	1296,0
Structural steel	54,0	7850,0	425,0	13422,0
Cerablanket	0,035	128,0	800,0	59,9
CaSi-board	0,069	450,0	748,0	151,9
Wood	0,1	450,0	1113,0	223,0
Brick	1,0	2000,0	1114,0	1521,0

Table 5-2: Material properties at ambient conditions (20 °C, 10% vol)

5.6 HEAT TRANSFER TO STRUCTURAL ELEMENTS

Various computer codes / models are available to calculate the temperature inside a compartment as a function of time. To know the temperature of the structural elements in function of time, it is necessary to calculate the heat flux to this element.

Convective and radiative heat transfer occur between the hot gases, the flame, the surrounding boundary constructions and the structural element. Emissivities and convection coefficients govern the heat transfer.

The heating up of a structural element depends on the type of element (e.g. pure steel or composite - steel / concrete) and of the nature and amount of fire protection.

At a given time (t), during the fire, the heat flux to a surface is given by:

$$\dot{h}_{net} = \dot{h}_c + \dot{h}_r$$

The convective heat transfer is mainly a function of the gas movement around the structural element and is given by:

$$\dot{h}_c = \alpha_c (\theta_g - \theta_m)$$

where:

α_c	is the convection coefficient	($W/m^2 \cdot K$)
θ_g	is the gas temperature	(^oC)
θ_m	is the structural element temperature	(^oC)

The radiative heat transfer is generally given by:

$$\dot{h}_r = \phi \cdot \varepsilon_f \cdot \varepsilon_s \cdot \sigma \left[(\theta_g + 273)^4 - (\theta_m + 273)^4 \right]$$

where :

ε_f	emissivity of the fire compartment (gas+boundaries),
ε_s	emissivity of the structural element
θ_g	temperature of the gas (K)
θ_m	temperature of the structural element (K)
σ	Boltzmann constant
ϕ	view factor

In standard ISO fire testing (furnaces) the resultant emissivity of the furnace (gas+walls) is about 0,8. The emissivity for unprotected steel is 0,625. The product $\varepsilon_f.\varepsilon_s$ is 0,5. Regarding the convection coefficients in the furnaces values are found varying from 25 to 50 (kW/m^2 , standard vs. hydrocarbon fire)

For the design based on natural fires the following values are suggested for the heat transfer to structural elements:

Convection coefficient:	35 $kW/m^2.K$
Emissivity of unprotected steel:	0,625
Emissivity of the compartment:	1

When rough methods are used to calculate the mechanical behaviour of structural elements (as critical temperature), the simple equations given above assuming a uniform temperature in the fire compartment are sufficient. When a mechanical model calculates the mechanical behaviour of the structure (global structural calculations), a more accurate model has to be used to calculate the heat transfer to structural elements and to determine temperature gradients.

6 STATISTICS

6.1 INTRODUCTION

Fire safety in buildings is a major concern of building regulations. At present in most countries detailed prescriptive regulations are given to the designer to be followed when designing a building. However, a strong move towards fire safety engineering and performance based regulations can be observed during the last years world wide.
The following statistical research aims at providing data on different aspects of fire safety to help engineers in their planing of fire safe buildings and the evaluation of their fire safety concept.
Moreover these statistics are the background of the γ factors on the fire loads.
These fire statistics have enabled to deduce probabilities of fire start, fire spread and failure of active fire fighting measures. In that way the influence on the fire of the compartment size, the building occupation and the different active fire fighting measures like sprinklers can be quantified in terms of probability. These probabilities have been used as data by the WG5 to deduce the γ factors on the fire loads.

6.2 DATABASE

This statistical WG4 report contains data from

- Switzerland : All the fires causing damage to the building larger than 700.000 ECU (40.000 fires) occurring between 1986 and 1995 in the Canton of Berne
- France:
    - fires in industrial buildings occurring between January 1983 to February 1984
    - all fire brigade intervention in 1995 (3.253.855 interventions of which 312.910 were for fires).

- The Netherlands: fires in industrial buildings occurring between January 1983 to January 1985
- Finland: All the building fires in 95 (2.109 fires for a total number of buildings of 1.150.494)
- The Luxembourg fire brigade reports for 1995 and 1997
  and international data from different sources on various aspects of fire safety namely sprinkler performance. Database on sprinkler effect were summarized or collected from USA, Finland, Germany, France, Australia and UK.

6.3 ANALYSIS AND INTERPRETATION OF DATA

6.3.1 FIRE OCCURRENCE AND FIRE GROWTH

On the basis of nearly 40.000 fires in Berne from 1986 to 1995 the frequency of fire occurrence and fire growth has been estimated in function of the size of loss to the building structure reported (see Table 6.1) and the floor area (Table 6.2).

	Dwellings			Industrial			Office / Public		
Fire loss class [CHF]	Sum of losses 10^6 CHF	%	Σ %	Sum of losses 10^6 CHF	%	Σ %	Sum of losses 10^6 CHF	%	Σ %
all	193,884	100	100	66,703	100	100	21,289	100	100
0 - 499	1,994	1,0	1,0	0,054	0,1	0,1	0,078	0,4	0,4
500 - 999	4,030	2,1	3,1	0,159	0,2	0,3	0,308	1,4	1,8
1.000 - 1.999	7,405	3,8	6,9	0,378	0,6	0,9	0,420	2,0	3,8
2.000 - 4.999	12,268	6,3	13,2	1,053	1,6	2,5	0,930	4,4	8,2
5.000 - 9.999	9,411	4,9	18,1	1,153	1,7	4,2	0,820	3,8	12,0
10.000 -19.999	10,044	5,2	23,3	1,624	2,5	6,7	0,892	4,2	16,2
20.000 -49.999	13,711	7,1	30,4	3,458	5,2	11,9	1,449	6,8	23,0
50.000 -99.999	13,139	6,8	37,2	4,255	6,4	18,3	1,139	5,3	28,3
100.000 -999.999	105,993	54,6	91,8	29,605	44,4	62,7	10,663	50,1	78,4
> 1.000.000	16,032	8,2	100	24,890	37,3	100	4,590	21,6	100

Table 6.1: Extend of fire damage (in 10^6 Swiss Francs) for different occupancies (1986-95)

Code	Occupancy	N° of buildings	Value CHF · 10^9	Height [m]	Value CHF/m^3	Floor Area m^2	%	∅ m^2/ build.
10	Office, public buildings	10.970	25,5	3	650	13.100.000	11	1194
20	Dwellings	161.190	121,3	2,7	600	74.900.000	61	465
30	Farms	84.930	25,6	8	375	8.500.000	7	100
40	Transport (stations, airport ...)	4.300	3,5	2,5	300	4.700.000	4	1093
50	Shops	4.010	6,8	4	700	2.100.000	2	524
60/70	Industrial buildings	5.450 /7.670	7,3/12,7	5	300	13.300.000	11	1013
80	Hotels	1.780	5,8	3,2	850	2.100.000	2	1180
90	Annex buildings (car parks ...)	62.210	1,5	2,5	350	2.200.000	2	35
	Total	342.510	205.6			120.900.000	100	353

Table 6.2: Estimated floor area per occupancy class calculated from the value at risk of each class and estimated data for room height and value per m^3 for the 1995 data.

Table 6.3 shows the frequency of fire occurrence and growth to a given loss size. For example the frequency of a fire to start in an industrial building was found as $11,6 \cdot 10^{-6}$ / (m^2 • year) and the frequency of fires to start and to grow as large as to cause a loss to the building structure of more than 99.999 CHF is $0,85 \cdot 10^{-6}$ / (m^2 • year). A decrease of the fire occurrence frequency with increasing compartmentation or building size was not studied, the frequencies are average values over the whole building group of Berne.

Loss-size	All [10^{-6}] / (m^2 • year)	Dwellings [10^{-6}] / (m^2 • year)	Office / Public [10^{-6}] / (m^2 • year)	Industrial [10^{-6}] / (m^2 • year)
All losses	32,3	33,3	10,60	11,6
> 1.999	9,18	9,22	4,35	6,48
>49.999	0,927	0,710	0,40	1,32
>99.999	0,641	0,460	0,27	0,85

Table 6.3: Frequency of fire occurrence and growth to a given loss size [per m^2 • year] for different occupancy classes

Data on the frequency of fire occurrence depends on the minimum size of fire that is counted in statistics as a fire. The data of Berne takes every reported fire into account even if there was no fire brigade action while insurance reports of industrial insurers with high excess do often include less fires than the fire brigade reports.

In Table 6.4 the values of the fire occurrence frequency for different occupancies in the Canton of Berne given in Table 6.3 are compared to data from other sources.

In V DIN 18230 (1987) and its background document [7, 11] the fire occurrence rate for industrial buildings was given as $2 \cdot 10^{-6}$/(m^2 • year) and has now been increased to $10 \cdot 10^{-6}/m^2$ in the 1996 draft edition E DIN 18230 [13].

Frequency of fire occurrence						
Country	All [10^{-6}] / (m^2 • year)	Dwellings [10^{-6}] / (m^2 • year)	Office / Public [10^{-6}] / (m^2 • year)	Industrial [10^{-6}] / (m^2 • year)	Number of registered fires	Remarks
Berne all > 1.999 > 49.999	32,3 9,18 0,93	33,3 9,22 0,71	10,6 4,35 0,40	11,6 6,48 1,32	39.104 in the Canton of Berne (1986-1995)	due to the monopoly all fires are included
FIN [14]	7,2	7,1	1,7 Public = 3,1 ... 9,5	11,0	2.109 (1995) total number of buildings 1.150.494	data only collected by the fire brigades (estimated 75% of all fires)
UK [15, 16]			12,0	66,0		
DIN 18230 (1987) [7] DIN 18230 (1996) [13]				2,0 10,0		There is no background on the information
France		21,2	8,9	7,9		

Table 6.4: Comparison of the Swiss data with other countries

The failure rate of limiting fire growth is estimated in Table 6.5. From the fact that only 40% of fires are attended by the fire brigade fires with a loss < 1.999 CHF are considered to be controlled by the occupants or were self-terminated. For the fire brigade the criterion control of fire could be related to a loss of < 49.999 CHF in general and for buildings with large compartments (industrial) to < 99.999 CHF.

failure rate of limiting the fire growth	All	Dwellings	Office / Public	Industrial
occupants e.g. fire loss > 1.999 CHF	28,4 %	27,7 %	41,0 %	56,1 %
fire brigade (one room) e.g. % of all the fires that grow to over a loss of 49.999 CHF if loss > 1.999 CHF	10,1 %	7,9 %	9,2 %	20,3 %
fire brigade (part of building) e.g. % of all the fires that grow to over a loss of 99.999 CHF if loss > 1.999 CHF	7,1 %	5,0 %	6,2 %	13,3 %

Table 6.5: Failure rate in limiting the fire growth

On this basis the fire brigade factor of 0,1 given in DIN 18230 [7] for industrial buildings seems to be justified (e.g. from Table 6.5 it can be seen that 13,3% of fire not controlled by occupants grow larger than 99.999 CHF in industrial buildings). In dwellings fire brigade success is even better.

6.3.2 SPRINKLER

The performance of sprinklers is often expressed in terms of the number of sprinkler heads opening in a fire. Based on the set of sprinkler data given in Table 36 of the WG4 report less than 30 heads will open in more than 99% of the cases. Taking into account even the cases with shot valves for well checked systems an overall reliability of 96 to 99% can be assumed. The value to be taken into account depends on various parameters (see e.g. Chapter 4.1.1 of the WG4 report). As a default value 98% seems appropriate.

This performance is higher than that of fire compartmentation especially if doors or other openings are present, because there is rarely a mandatory periodical maintenance and inspection for passive measures. Even though limited in number and restricted to large losses the Dutch data shows that from the 23 cases where compartmentation was present it failed in 11 cases e.g. 48%, while in none of the cases a sprinkler failed.

6.4 RECOMMENDATIONS

6.4.1 FIRE OCCURRENCE AND FIRE GROWTH

The probability of a severe fire able to endanger the structural stability may be expressed as:

$$p_{fi} = p_1 \cdot A^x \cdot p_2$$

with: p_1 : probability of severe fire including the effect of the occupants and a public fire brigade
p_2 : reduction factor if sprinkler system is present
A : surface area of compartment
x : exponent ≤ 1.0

Note: The factor p_1 includes the actions of the occupants and the public fire brigade in preventing a fire to grow into a severe fire and is not to be mistaken as the frequency of fire occurrence.

For the application in the NFSC method the following default values are recommended.

Occupancy	p_1 [10^{-6}/(m^2 ·year)]	Exponent x
Office	0,2 - 0,4	0,75 - 1,0
Dwelling	0,4 - 0,9	1,0
Industrial	0,5 - 1,0	0,3 - 1,0

Table 6.6: Probability of fire start and growth to severe fire with public fire brigade present

Reduction factor for sprinkler system:

Type of sprinkler	p_2
Normal (e.g. according to the regulations)	0,02
High standard (e.g. electronically checked valve, two independent water sources)	0,01 - 0,005
Low standard (e.g. not according to the regulations)	≥ 0,05

Table 6.7: Reduction factor for sprinkler system

6.4.2 EVENT TREE ANALYSIS

Alternatively an event tree may be established from fire start to describe fire growth, using recommended default values from Table 6.8.

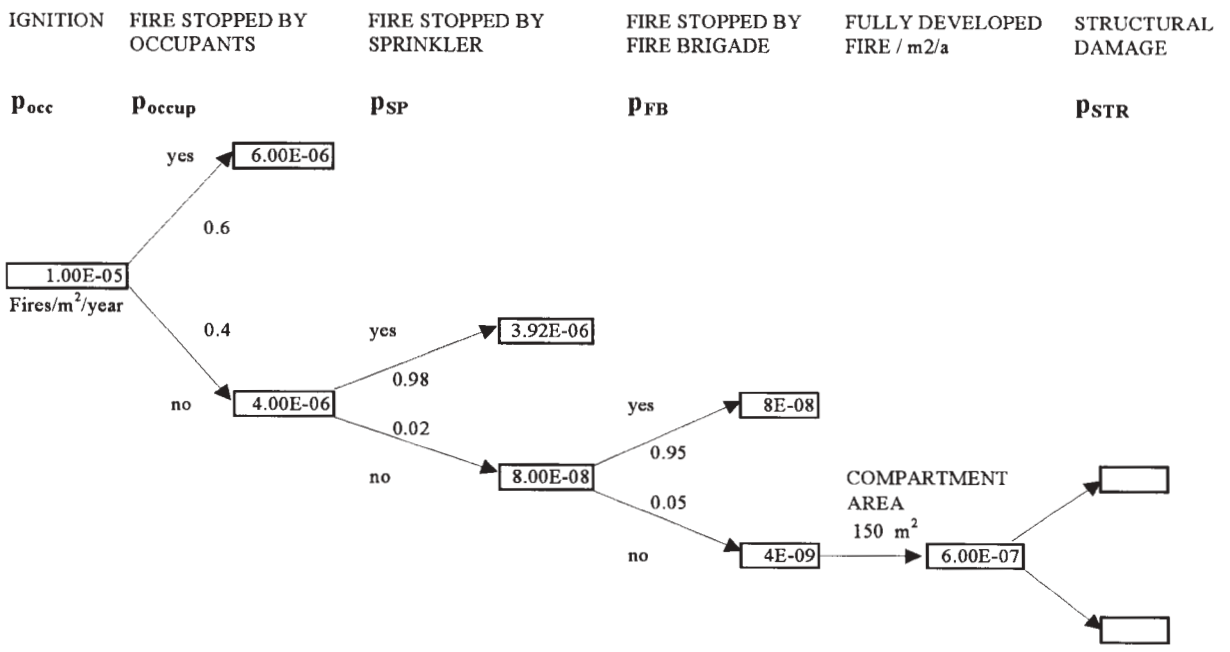


Figure 6.1: Example for an event tree for fire growth in an office with a compartment area of 150 m^2

From Tables 6.3, 6.5 and 6.7 the following factors may be recommended:

	[1/(m².year)]	Dwelling	Office	Industrial
Fire occurrence	p_{occ}	$30 \cdot 10^{-6}$	$10 \cdot 10^{-6}$	$10 \cdot 10^{-6}$
Fire stopped by occupant	p_{occup}	0,75	0,60	0,45
Fire stopped by sprinkler system	p_{SP}			
Fire stopped by fire brigade	p_{FB}	0,90 - 0,95	0,90 - 0,95	0,80 - 0,90
Fire confined by structure	p_{STR}			

Table 6.8: Event tree factors

P_{FB}, the probability that the Standard Fire Brigade manage to stop the fire, is between 0,9 and 0,95 for Offices according to the Statistics. During the Advisory Committee, some experts proposed to consider different values of P_{FB} depending on the firemen ability and the intervention time.
In addition to P_{FB}, the Table 6.9 gives between brackets the value of N which is the probability reduction of having a fully developed fire due to the action of the firemen

$$\left(N = \frac{1}{1 - P_{FB}} \right)$$

Time between Alarm and Action of the FIREMEN	**< 10'**	**< 20'**	**< 30'**	**> 30'**
Type of FIREMEN				
Professional	**0,95** (20)	**0,9** (10)	**0,8** (5)	**0,001** (1)
Not-Professional	**0,9** (10)	**0,8** (5)	**0,001** (1)	**0,001** (1)

Table 6.9: P_{FB} for Office (Reduction N of the fully developed fire probability due to FB)

In case of Automatic fire Detection by Smoke (ADS) and Automatic Alarm Transmission (AAT), the Table 6.9 becomes

Time between Alarm and Action of the FIREMEN	**< 10'**	**< 20'**	**< 30'**	**> 30'**
Type of FIREMEN				
Professional	**0,98** (80)	**0,97** (40)	**0,95** (20)	**0,001** (1)
Not-Professional	**0,97** (40)	**0,95** (20)	**0,75** (4)	**0,001** (1)

Table 6.10: P_{FB} for Office (Reduction N of the fully developed fire probability due to FB) in case of ADS and AAT.

7 WORKING GROUP 5 : METHODOLOGY TO DEDUCE FROM THE PROBABILITY

7.1 INTRODUCTION

The probability that a fire breaks out in a swimming-pool is obviously much lower than in a painting workshop. Moreover the probability that this starting fire spreads and leads to a fully engulfed compartment depends on the compartment area and of course on the active fire fighting measures such as the sprinklers which may extinguish automatically the fire, the firemen or the automatic fire detection (by smoke or heat) and the automatic transmission of the alarm to the firemen which allows a rapid fire brigade intervention.

The WG4 has collected statistics and has deduced the probability that:

- a fire starts (see Tables 6.3 and 6.8)
- the occupants fail in stopping the fire (see Tables 6.3 and 6.8)
- the firemen do not succeed in stopping the fire (see Tables 6.5, 6.8, 6.9 and 6.10)
- the automatic active measures to extinguish the fire (sprinkler) fail in stopping the fire (see Table 6.7)

From those probabilities it is possible to deduce γ factors on the fire load by a procedure described in this chapter WG5 and based on the Annex A of ENV 1991-1[17] and reliability calculations.

This factor has been divided into subcoefficients γ_{q1}, γ_{q2}, γ_{ni} to take into account the compartment size, the building type and the different active fire fighting measures like sprinklers.

The characteristic fire load $q_{k,f}$ (see Table 5.1) has to be multiplied by

$\gamma_{qf} = \gamma_{q1} \times \gamma_{q2} \times \gamma_{ni}$ to obtain the design fire load $q_{d,f}$.

The design fire load is then used by the tool developed by WG1 (OZONE) to calculate the design natural fire curve.

7.2 DETERMINATION OF THE DESIGN VALUES AND SAFETY FACTOR γ IN THE EUROCODES - PRINCIPLE

The resistance R and the Action S are according to statistical distributions which are defined by the standard deviation and the mean. To ensure a sufficient safety, it is necessary that the failure (S > R) occurs only with a very low probability given by the hatched area (see Figure 7.1). This area can be measured by the safety index β.

The Eurocode gives a failure probability of $7{,}23.10^{-5}$ for the building life, which corresponds to a safety index β of 3,8.

However, there are a lot of actions: (self weight, variable load, snow, wind, earthquake, fire..) and a lot of resistances (compressive strength of concrete, yield point of the steel of the profiles, rebars, bending resistance, buckling resistance...).

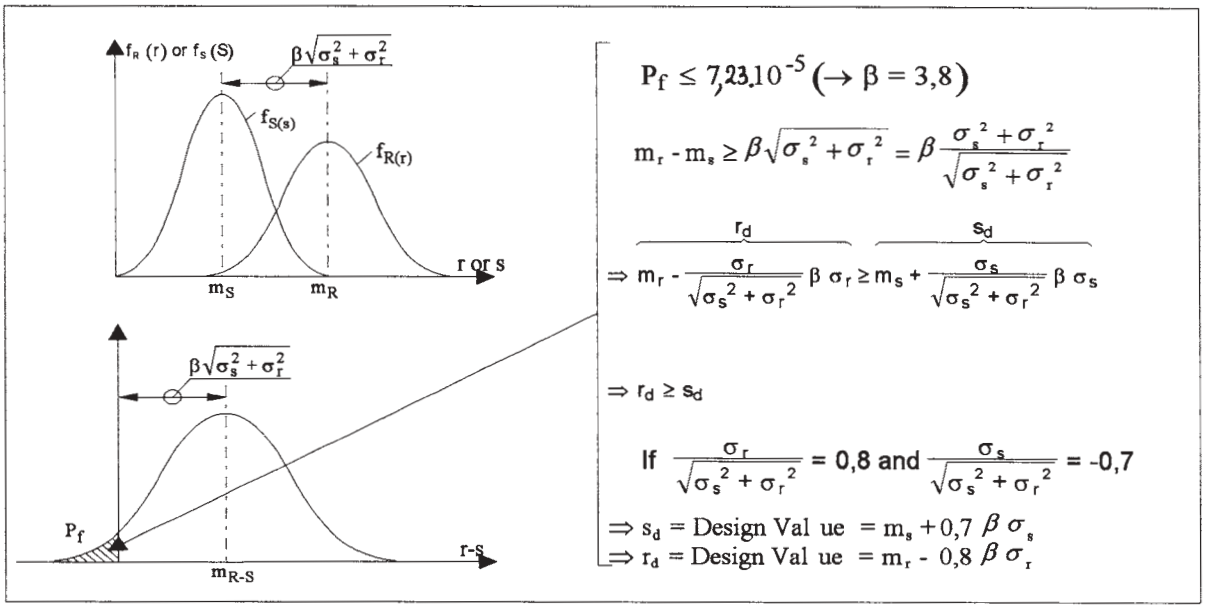


Figure 7.1

Therefore the problem is much more complex than the comparison between two statistical variables. That's why the Eurocodes have adopted a semi-probabilistic approach based on the FORM method (First Order Reliability Method).

This simplification of the Eurocodes consists of assuming:

$$\alpha_R = \frac{\sigma_R}{\sqrt{\sigma_R^2+\sigma_S^2}} = 0{,}8 \text{ for the resistance.}$$

$$\alpha_S = \frac{\sigma_S}{\sqrt{\sigma_R^2+\sigma_S^2}} = (-0{,}7) \text{ for the main action and } (-0{,}28) \text{ for the secondary action}$$

By considering constant values for the weighing factors α_{si}, the design values s_d for actions can be defined without referring to the resistance, as these design values depends only on the safety index β, on the standard deviation of the statistical distribution of the action and, of course, on the type of the distribution (see Table A3 and equations A.3a, A.3b, A.4.a and A.4.b of ENV 1991-1 [17]).

This design value s_d of one action is thus the value of the action which has to be considered in order to obtain the required safety. If β is equal to 3,8 as in the Eurocode, this implies that the failure risk is equal to $7{,}23.10^{-5}$ during the building life. As a consequence, for each action, it is possible to define safety coefficient γ which is the ratio between the design value s_d and the characteristic value, which is the usual reference value :

$$\gamma = \frac{s_d}{s_k}$$

In this way we can find the safety coefficients given in the Eurocodes : on the action side 1,35 and 1,5 for the self weight and the imposed loads; on the resistance side 1,1 , 1,15 and 1,5 for respectively structural steel, reinforcement bars and concrete.

7.2.1 SELF WEIGHT [17, 18(CHAPTER 9), 19]

- $\beta = 3{,}8$; $\alpha = -0{,}7$
- Statistical law : Gaussian
- Variation coefficient $V_G = \frac{\sigma_G}{m_G} = 0{,}1$

  with σ_G the standard deviation and
  m_G the mean
- γ_{sd} : safety factor for the model for calculating the action effects = 1,05.
- Design value : $G_d = \gamma_{sD}\,(m_G - \alpha\beta\sigma_G)$

  $= 1{,}05\ m_G\ (1 + 0{,}7\,.\,3{,}8\,.\,V_G)$

  $= 1{,}05\ m_G\ (1 + 0{,}7\,.\,3{,}8\,.\,0{,}1)$

  $= 1{,}33\ m_G$
- Characteristic value G_k : it is normally taken from the nominal values of the dimensions and the density. Hence G_k is the mean value :

$$G_k = m_G$$

- Safety factor : $\gamma_G = \frac{G_d}{G_k} = \frac{1{,}33\ m_G}{m_G} = 1{,}33$

7.2.2 VARIABLE LOADS [17, 18(CHAPTER 9), 19]

- $\beta = 3,8$; $\alpha = -0,7$
- Statistical law : Gumbel type I
- Variation coefficient $V_Q = \frac{\sigma_Q}{m_Q} = 0,3$

  with σ_G the standard deviation and
  m_G the mean
- γ_{sd} : safety factor for the model for calculating the action effects = 1,05.
- Design value : $Q_d = \gamma_{sD} \left\{ u - a^{-1} \ln[-\ln \phi(-\alpha \beta)] \right\}$

  with $u = m_Q - \frac{0,577}{a}$;

  ϕ, the distribution function of the normal distribution

  and $a = \frac{\pi}{(\sigma_Q \sqrt{6})}$

$$Q_d = 1,05\ m_Q \left\{ 1 - \frac{\sqrt{6}}{\pi} V_Q \left(0,577 + \ln\left[-\ln \phi\ (-\alpha \beta)\right]\right) \right\}$$

$$Q_d = 1,05\ m_Q \left\{ 1 - \frac{\sqrt{6}}{\pi} V_Q \left(0,577 + \ln\left[-\ln \phi\ (0,7 \beta)\right]\right) \right\}$$

- Characteristic value Q_k corresponding to the 95 % fractile value

$$Q_k = m_Q \left\{ 1 - \frac{\sqrt{6}}{\pi} V_Q \left(0,577 + \ln\left[-\ln (0,95)\right]\right) \right\}$$

- Safety factor :

$$\gamma_Q = \frac{Q_d}{Q_k} = 1,05 \frac{\left\{ 1 - \frac{\sqrt{6}}{\pi} V_Q \left(0,577 + \ln\left[-\ln \phi\ (0,7 \beta)\right]\right) \right\}}{\left\{ 1 - \frac{\sqrt{6}}{\pi} V_Q \left(0,577 + \ln\left[-\ln (0,95)\right]\right) \right\}} = 1,46$$

7.2.3 STRUCTURAL STEEL [17, 19]

- $\beta = 3,8$; $\alpha = 0,8$
- Statistical law : Lognormal
- Variation coefficients :

V_R = coefficient of variation for the Design Value = $\sqrt{V_G^2 + V_m^2 + V_f^2} = 0,052$
V_m = coefficient of variation for Model uncertainly = 0,03
V_G = coefficient of variation for Geometry of element = 0,03
V_f = coefficient of variation for property = 0,03

- Design value : $X_d = m_X \exp(-\alpha_R \beta V_R)$
$= m_X \exp(-0,8 \beta V_R)$
- Characteristic value : $X_k = m_X \exp(-k V_f)$
with k = 1,645 corresponding to the 5 % fractile
- Safety Factor : $\gamma_a = \frac{X_k}{X_d} = \exp(0,8 \beta V_R - k V_f)$
$= \exp(0,8 \cdot 3,8 \cdot 0,052 - 1,645 \cdot 0,03)$
$= 1,11$

7.2.4 FIRE LOAD [17, 19]

The fire load may also be considered as an action. However this action is an accidental action so that the target value in case of fire $p_{t,fi}$ is equal to the ratio of p_t , the target value probability and p_{acc} , the probability that the accidental action occurs :

$$p_{t,fi} = \frac{p_t}{p_{acc}}$$ (see Chapter 4.2.4 of [18])

- In that way, the safety index β_{fi} is no more the fixed value 3,8 but depends on the different factor influencing p_{acc} (building occupancy types, fire compartment area, active fire fighting measures) : $\beta_{fi} = f(p_{t,fi})$
- Assuming that the fire load is the main action in case of fire, the weighing factor α for the fire load is -0,7 : $\alpha_{qf} = -0,7$. Reliability calculations (see chapter 7.4) points out that this starting assumption should be modified ($\alpha_{qf} = -0,9$). Moreover that calculation shows that the weighing factor for the main action at room temperature is strongly reduced in case of fire and may therefore considered as a secondary action.
- Statistical law : Gumbel type I.

According to the fire load densities given in the U.K. document "The Application of Fire Safety Engineering Principles to the Safety in Buildings" [8] and Prof. Fontana's analyse [20], the data of fire loads fit well into a Gumbel type I distribution. That's why the Gumbel distribution has been used here as well as in WG3 and WG5 reports. However the procedure of this paper could be easily applied with another statistical law (lognormal ...).

- $\gamma_{sD} = 1{,}05$
- Variation Coefficient : $V_{qf} = 0{,}25$ [8]
- Design Value (see variable loads) :

$$q_{f,d} = 1{,}05\, m_{qf} \left\{1 - \frac{\sqrt{6}}{\pi} V_{qf}\left[0{,}577 + \ln\left(-\ln \phi(-0{,}7\,\beta)\right)\right]\right\}$$

- Characteristic value $q_{f,d}$ corresponding to 80 % fractile (see Annex D of ENV 1991-1-2 [3] and WG3 and WG5 reports).
- Factor γ_{qf}

$$\gamma_{qf} = \frac{q_{f,d}}{q_{f,k}} = 1{,}05 \frac{\left\{1 - \frac{\sqrt{6}}{\pi} V_{qf}\left[0{,}577 + \ln\left(-\ln \phi(-0{,}7\,\beta)\right)\right]\right\}}{\left\{1 - \frac{\sqrt{6}}{\pi} V_{qf}\left[0{,}577 + \ln\left(-\ln 0{,}8\right)\right]\right\}}$$

$$= 1{,}75 \text{ for } \beta = 3{,}8$$

The evolution of γ_{qf} as a function of β is given by the Figure 7.2.

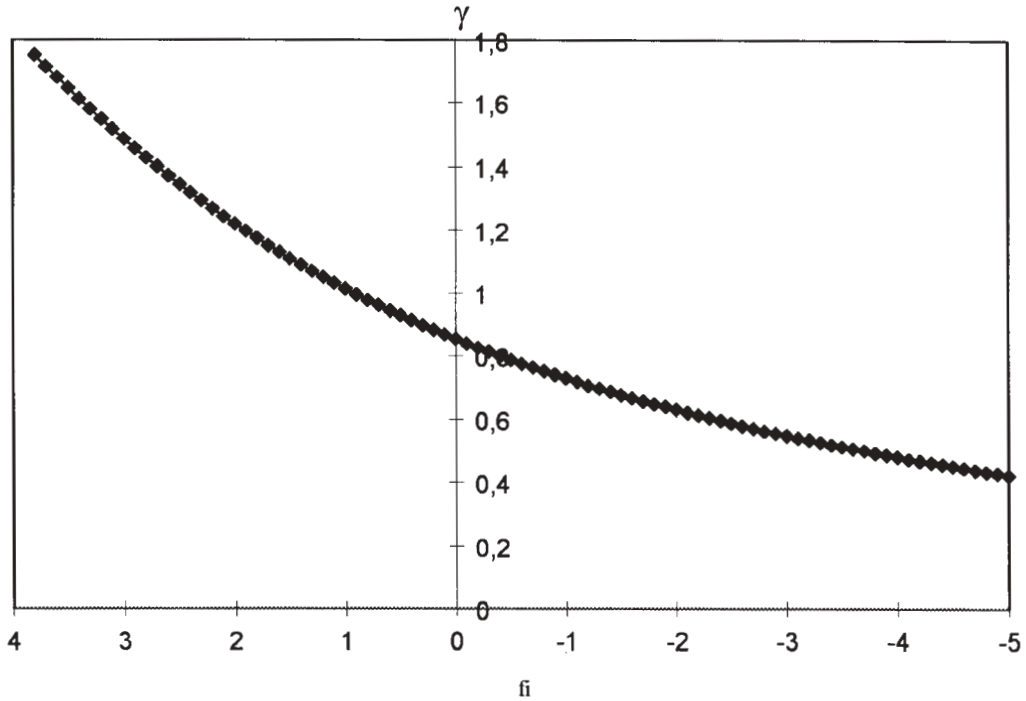


Figure 7.2 : Safety factor γ_{qf} as a function of β

Knowing the probability of a general fire (Fully Engulfed fire Compartment) depending on the fire compartment size, the type of occupancy and the active fire fighting measures, the safety index β_{fi} depending on the target failure value p_t divided by the probability of a general fire, p_{acc} can be deduced.

$$\beta_{fi} = \phi^{-1}\left(\frac{p_t}{p_{acc}}\right) = \phi^{-1}\left(\frac{7{,}23.10^{-5}}{p_{acc}}\right)$$

The Figure 7.2 enables then to deduce the factor γ_{qf} for the fire load.

However this global procedure implies the calculation of the fire probability for each case. That's why we have proposed a simplified approach which consists of splitting the safety factor $\gamma_{fire\ load}$ into 3 coefficients γ_{q1} to consider the compartment size, γ_{q2} to consider the risk of fire activation and γ_{ni} to take into account the influence of the active measures.

7.3 DETERMINATION OF THE DIFFERENTIATION FACTORS γ_{Q1}, γ_{Q2} AND γ_{QN} BY EXTENDING THE ANNEX A OF ENV 1991-1 [17]

7.3.1 REFERENCE CASE

According to the background of the DIN 18230 [11], the probability to have a fully engulfed compartment per m^2 per year in the schools, hotels or offices is equal to 5.10^{-7}. According to the WG4 report, this value is between 2 and 4.10^{-7} (see Table 6.6) This probability can be divided into p_1, probability that the fire starts and p_2, probability that this starting fire turns to a flash-over.

By multiplying by 50, we obtain the probability for the complete life of the building estimated to 50 years : probability of a compartment fully engulfed by the fire :

$$p_1\, p_2 = 5\ .\ 10^{-7}\ .\ 50 = 25\ .\ 10^{-6}$$

If we consider a fire compartment of 25 m^2 (A_f), the probability p_{acc} of a fully engulfed fire compartment is :

$$p_{acc} = p_1\, p_2\, A_f = 6{,}25\ .\ 10^{-4}$$

The target value of the failure becomes then :

$\frac{p_t}{p_{acc}} = \frac{7{,}23.10^{-5}}{6{,}25.10^{-4}} = \mathbf{0{,}116}$ and the corresponding safety index β_{fi} is equal to 1,2.

This factor β_{fi} of 1,2 implies a safety factor γ of 1,0 in case of 80 % fractile for the characteristic fire load. This safety factor corresponding to the reference case will be noted γ_{ref}.

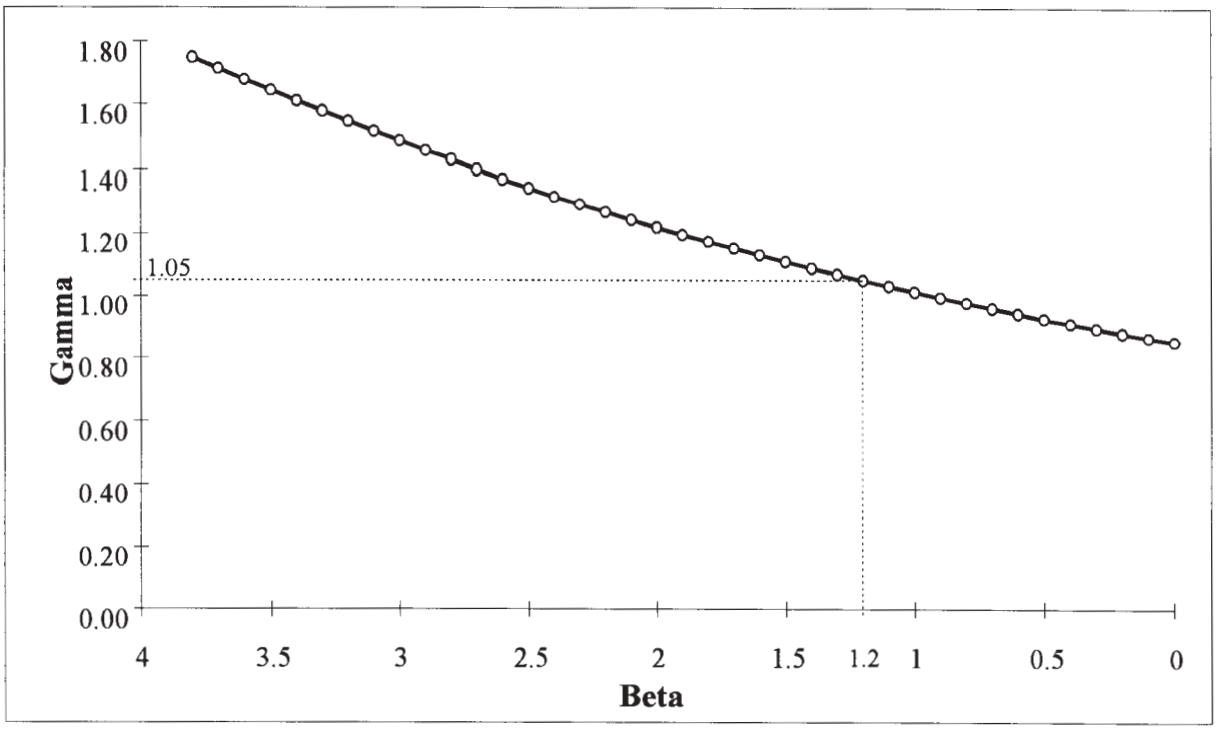


Figure 7.3 : Safety Factor γ on the Fire Load corresponding to a characteristic value of 80% fractile.

7.3.2 DIFFERENTIATION FACTOR γ_{Q1} - INFLUENCE OF THE COMPARTMENT AREA

In the same way, we can obtain other safety coefficients γ for other areas A_f.

A_f [m^2]	λ_b	P_t / λ_b	β_{fi}	γ	$\gamma_{q1} = \gamma/\gamma_{ref}$
25	$6{,}25 \cdot 10^{-4}$	0,11600	1,22	1,0	1,0
250	$6{,}25 \cdot 10^{-3}$	0,01160	2,28	1,25	1,25
2500	$6{,}25 \cdot 10^{-2}$	0,00116	3,03	1,5	1,5
5000	$12{,}5 \cdot 10^{-2}$	0,00052	3,26	1,6	1,6
10000	$25 \cdot 10^{-2}$	0,00029	3,45	1,65	1,65

Table 7.1

Let's call γ_{q1} the factor γ divided by the safety factor of the reference γ_{ref}.

7.3.3 DIFFERENTIATION FACTOR γ_{Q2} - INFLUENCE OF THE RISK OF FIRE ACTIVATION

The previous calculation is based on a probability of fire p_1 p_2 of 5.10^{-7} per year and m^2.

This value corresponds to schools, offices or hotels. It is obvious that the risk is much higher for a fireworks industry and lower for a museum with Grecian statues.

For a building of 2.500 m², the safety coefficient γ is equal to 1,5 [see Table 7.1]. What happens if the probability of having a fire is reduced by 10 ? The Figure 7.4 shows that the safety coefficient γ is reduced by a factor 0,85.

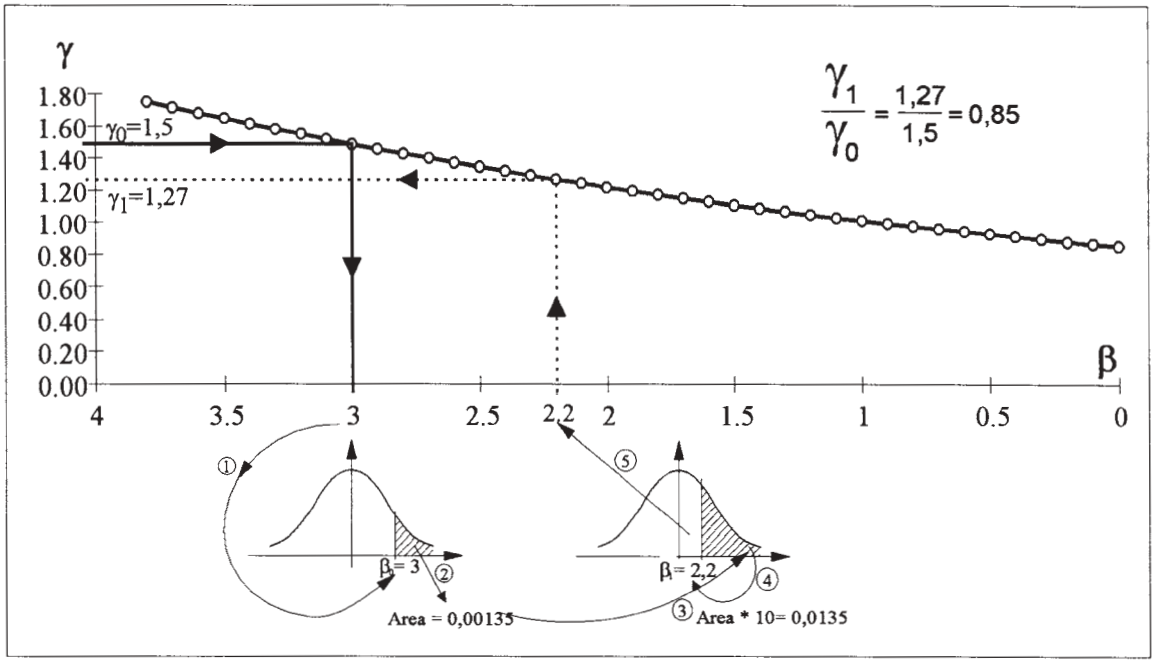


Figure 7.4

Moreover, the Figure 7.5 shows that this factor 0,85 doesn't change a lot if we make a variation on the starting point β_0.

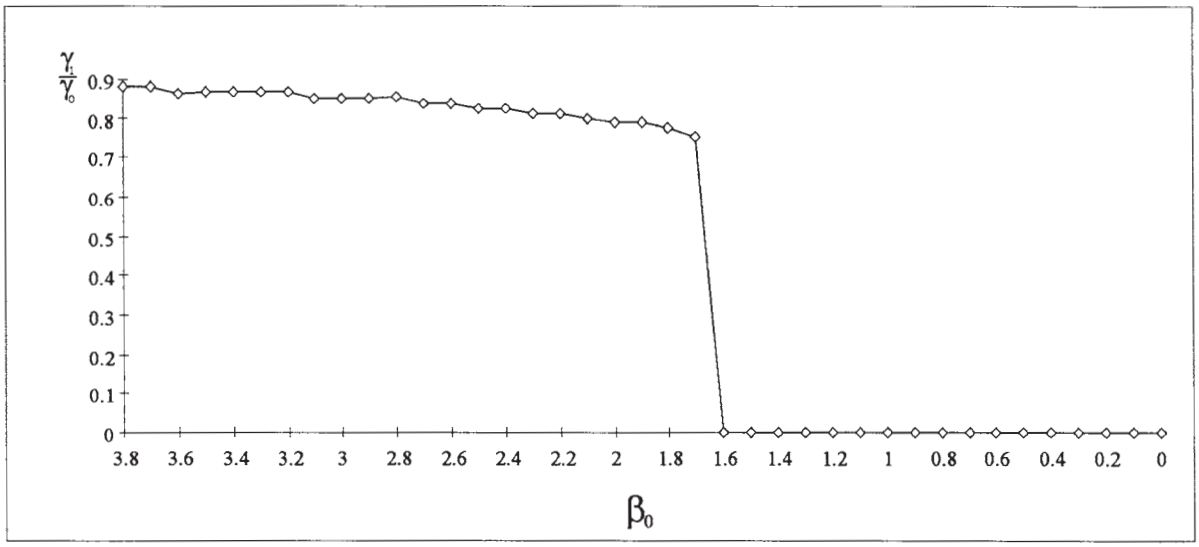


Figure 7.5

In this way, the buildings can be classified according to the danger of fire activation. For instance, the category 2 (Hotel, School, Office) has a danger of fire activation 10 times higher than the category 1 (Museum, Art Gallery) and 10 times lower than the category 3 (Engine Fabrication). For each class, it is possible to deduce an additional safety coefficient γ_{q2} which has to multiply the coefficient γ_{ref} and the factor γ_{q1} of the previous table.

Type of building Destination	Danger of fire activation	$N = \frac{(p_{acc})}{(p_{acc,ref})}$	$\gamma_{q2} = \frac{\gamma}{\gamma_{ref}}$
Museum, Art gallery	Low	10^{-1}	0,85
Hotel, School, Office	Normal	1	1
Engine Fabrication	Average	10	1,2 ($\cong 1 / 0,85$)
Painting Workshop Chemistry Laboratory	High	100	1,4 ($\cong 1 / 0,85^2$)
Painting Fabrication Fireworks Industry	Higher	1000	1,6 ($\cong 1 / 0,85^3$)

Table 7.2

7.3.4 DIFFERENTIATION FACTOR γ_N - INFLUENCE OF THE ACTIVE FIRE FIGHTING MEASURES

In the same way, the influence of active fire fighting measures can be quantified. Each active measure reduces the probability p_{acc} that a starting fire turns to a flash-over or a fully engulfment of the compartment by a factor N. Therefore, for each active measure it is possible to deduce a coefficient γ_n smaller than 1 to take into account the sprinklers, the firemen or the detection measures.

The Figure 7.6 is similar to the Figure 7.5 but other fire probability reductions N have been considered. The Figure 7.6 can also be represented by the Figure 7.7.

These Figures 7.6 and 7.7 attest that the factors γ_{ni} don't depend very much on the starting point β_0; the γ_{ni} are more or less constant as a function of β_0 up to a given β_0 for which the value of γ_{ni} drops down to zero. This drop to zero means that the effect of the active measure is such that the fire probability becomes smaller than the target failure probability.

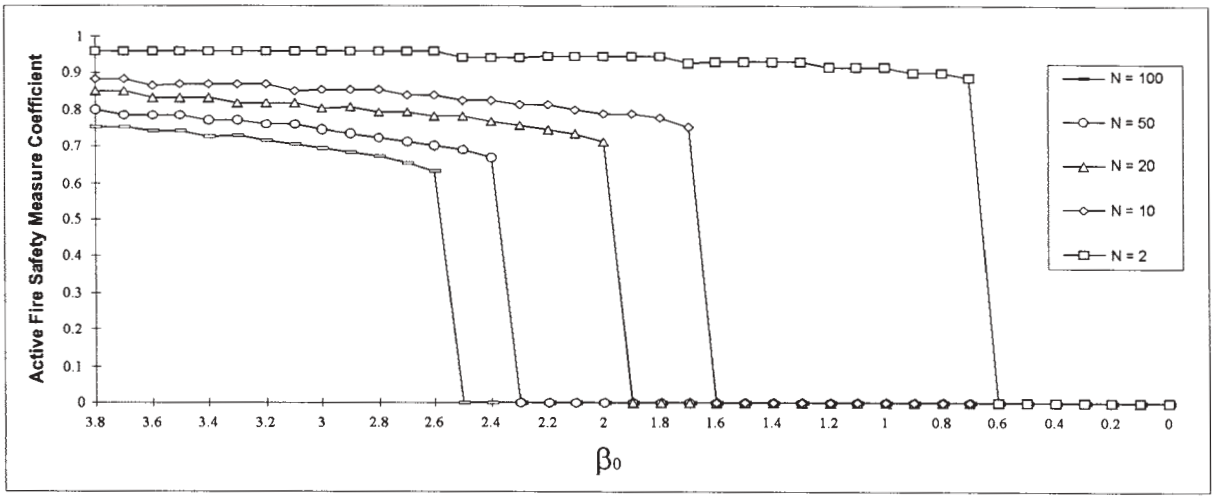


Figure 7.6 : Active Fire Safety Measure Coefficient

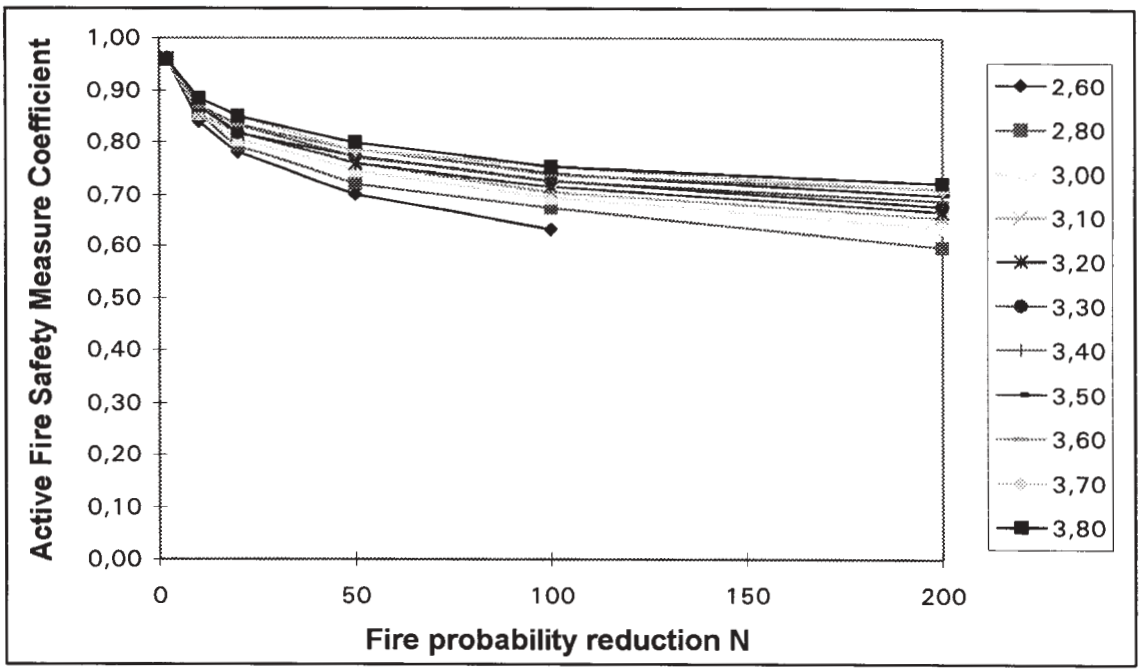


Figure 7.7

These Figures 7.6 and 7.7 enables to deduce the Table 7.3 which shows for each active measure the corresponding reduction of fire probability N and the corresponding factor γ_n.

	Active Measures (A.M)	N	γ_n	γ_{ni}
Automatic Suppression	Sprinkler (S)	100	0,7	0,7
	S + 1 independent Water Supply	100*2	$\gamma_{sprinkler}$*0,95	0,95
	S + 2 independent Water Supply	100*4	$\gamma_{sprinkler}$*0,9	0,9
Manual Fire Suppression	Work Fire Brigade (WFB)	100	0,7	0,7
	Standard Fire Brigade (SFB)	10	0,85	0,85
	SFB + Automatic fire detection by heat	10*4	γ_{SFB}*0,9	0,9
	SFB + Automatic fire detection by smoke (ADS)	10*16	γ_{SFB}*0,8	0,8
	SFB + ADS + Automatic Alarm Transmission to fire Brigade	160*4	$\gamma_{SFB+ADS}$*0,9	0,9
	Fire Fighting Devices (Extinguishers, Hydrants)	10^{-2}	1 / 0,7	1,4

Table 7.3

When some **elementary** fire fighting active measures, as for example a sufficient number of hand extinguishers at each storey are not present, the probability of a fire spread is higher than as usual, which implies a coefficient γ_n greater than 1 (see last line of Table 7.3).

7.4 STUDY OF THE NEW METHODOLOGY BY USING RELIABILITY CALCULATIONS (FORM METHOD) WITH THE SOTFWARE VAP [22]

Introduction

The previous Chapter has been based on the Annex A of ENV 1991-1 [17] which assumes a weighing factor α of (-0,7) for the main action and (-0,28) for the secondary action. The fire load density has been considered as the main action. In order to check these assumptions and also to analyse the problem more in details, it was decided to use the reliability method FORM which considers the statistical distribution of each variable, calculates the weighing factor α_i for each variable and deduces the safety index and the corresponding failure probability. The method FORM (First Order Reliability Method) is referred in ENV 1991-1 [17].

The program VAP [22] which enables to deal with the FORM method in an interactive, easy and quick way has been used by the WG5 partners to analyse 4 structure types: unprotected steel beam [Book 2: Part 5 Chapter 4.1 of the WG5 by PA-RE], unprotected steel column [Book 2: Part 5 Chapter 4.2 of the WG5 by ETH], protected steel beam [Book 2: Part 5 Chapter 4.3 of the WG5 by CTICM] and protected steel column [Book 2: Part 5 Chapter 4.4 of the WG5 by ETH].

In this main part, only the case of unprotected steel beam has been described (see WG5 report for the other types of structures).

7.4.1 UNPROTECTED STEEL BEAM

7.4.1.1 Introduction

Reliability methods applied commonly for the persistent design situation may be also used to analyse the accidental (fire) design situation. An example of the steel beam supporting a floor of an office area is used throughout this Chapter 7.4.1. Using partial factor methods as specified in Eurocodes 1 and 3 [3, 17, 23] and ISO 834 [24], the steel beam is firstly designed for both the persistent and accidental (fire) design situation. Then its reliability in the strength domain is analysed using the First Order Reliability Method (FORM [22]).

7.4.1.2 Deterministic design

A simple supported steel beam of a span L exposed to the permanent load G and imposed load Q is considered in the reliability analysis below. In accordance with the Structural Eurocodes [3], [17] and [23] reliability of the beam at the persistent and accidental (fire) design situation should be verified using appropriate load combination and partial safety factors. The following condition should be valid at the persistent design situation

$$(\gamma_G G_k + \gamma_Q Q_k) L^2/8 < W f_{yk}/\gamma_m \qquad (7.1)$$

where notations and numerical values recommended by Eurocodes are applied in this Chapter: γ_G = 1,35 denotes the partial safety factor of permanent load G, G_k characteristic value of G, γ_Q = 1,5 partial safety factor of variable load Q, Q_k characteristic value of Q, L is span of the beam, W_{pl} is section modulus, f_{yk} the characteristic value of yield strength f_y, γ_m = 1,1 the partial factor of material property.

As an example (used throughout this Chapter) consider the steel beam supporting a floor of an office area having the following input data

$$L = 6 \text{ m}, G_k = 12 \text{ kN/m}, Q_k = 9 \text{ kN/m}, f_{yk} = 235 \text{ MPa} \tag{7.2}$$

which correspond to the loading width 3 m for an office area having the characteristic imposed load 3 kN/m^2. Using data (7.2), it follows from equation (7.1) that the section modulus 625,6 cm^3 is required considering the persistent design situation (not accidental - fire design situation). As an example profile IPE A 330 having W = 701,9 cm^3 may be considered in the design.

In the following reliability consideration the actual profiles are not taken into account and theoretical values of section modulus are considered. However, due to serviceability requirements (deflection, vibration), due to limited choice of "standardised profiles" and, in order to avoid too many different cross sections in the same building, practical design would always lead to a greater sectional modulus than the minimum value. It is reasonable to assume that the actual modulus will be about double of the minimum value determined considering persistent design situation and ultimate limit state only. That's why the section modulus 2 * 625,6 = 1.251,2 cm^3 is considered in the following analysis of the example of simply supported beam (note that it would require the profile IPE 400 having W_{pl} = 1.307 cm^3).

At the accidental (fire) design situation the following condition is to be considered

$$(G_k + \psi_{1,1} Q_k) L^2/8 < W_{pl} f_{yk} k_y / \gamma_{M,fi} \tag{7.3}$$

where no partial factors γ are used (all partial factors equal unity) while the combination factor $\psi_{1,1}$ = 0,5 may be applied in accordance with equation (9.11) in [17]. The reduction factor k_y of the yield point is introduced in accordance with [23]. It follows from (7.2) and (7.3) that the reduction factor k_y used at the fire design situation should satisfy the condition

$$(G_k + \psi_{1,1} Q_k) * (L^2/8) / (1.251{,}2 * f_{yk} / \gamma_{M,fi}) < k_y \tag{7.4}$$

Using data (7.2) and $\gamma_{M,fi}$ = 1 the minimum reduction factor following from equation (7.4) is k_y = 0,2525. However, it follows from (4.18) in ENV 1993-1-2 [23] that the reduction factor k_y of the yield point is a function of the temperature θ.

$$k_y = (0{,}9674\ ((1+\exp((\theta - 482)/39{,}19))))^{(-1/3{,}833)} \qquad (7.5)$$

where θ denotes the temperature in the steel. Using data (7.2) and equations (7.4) and (7.5) it follows that the critical temperature θ_{cr} is 690 °C

Taking into account the equation (B.1) in ENV 1991-2-2 [3] improved such that

$\theta_{air} = 20$ for t=0,

$$\theta_{air} = 20 + 1.325*(1-0{,}324*\exp(-0{,}2*t/60)-0{,}204*\exp(-1{,}7*t/60)-0{,}472*\exp(-19*t/60)) \qquad (7.6)$$

where t is given in minutes, it follows that t is about 9,40 minutes (0,1565 hour) for $\theta_{air} = 690°C$.

In the following equivalent fire load intensity is recalculated assuming the EC fire curve given by equation (7.6) taking into account data (7.2) supplemented by other required parameters describing a given fire compartment. Further, it is assumed that the maximum steel temperature θ is equal to the maximum air temperature θ_{air} inside the fire-affected compartment, which is on the safe side. Then the corresponding fire load intensity may be calculated from the equation given in Annex B of ENV 1991-2-2 [3] for time t (in hours)

$$t = 0{,}00013\ q_{t,d}\ \Gamma / O \qquad (7.7)$$

where the factor $\Gamma = (O/b)^2/(0{,}04/1.160)^2$ defined in Annex B of ENV 1991-2-2 [3] is equal to 1 as the following parameters are considered for the sake of simplicity: the opening factor O = 0,04 $m^{1/2}$ and the factor of the thermal properties of walls is b = 1.160 J/ (m^2 $s^{1/2}$ K). Considering the given input data (7.2), equation (7.7) leads to the design value of fire load intensity related to the total surface area A_t as

$$q_{t,d} = 0{,}1565 \times 0{,}04 / 0{,}00013 = 48{,}16\ [MJ/m^2] \qquad (7.8)$$

The design value $q_{f,d}$ of fire load intensity related to the floor surface area A_f is calculated using expression taken from Annex B of [3]

$$q_{f,d} = q_{t,d}\ A_t/A_f = 48{,}16 \times 4 = 192{,}7\ [MJ/m^2] \qquad (7.9)$$

where A_t/A_f = 4 is the assumed ratio of the total and floor surface area of the fire compartment.

Equation (7.9) gives the maximum design value $q_{f,d}$ of fire load intensity which is acceptable in the given office area for the beam designed considering the persistent design situation with a load level of approximately 0,5 (having the section modulus 1.251,2 cm^3, which is the double of the minimum value required 625,6 cm^3).

7.4.1.3 Reliability analysis

The limit state function in the persistent as well as accidental (fire) design situation may be written as

$$Z = \xi_R R - \xi_E E \tag{7.10}$$

where Z denotes the safety margin, ξ_R the coefficient of model uncertainty for the resistance R and ξ_E the coefficient of model uncertainty for the load effect E.

The resistance R at the persistent design situation is given as

$$R = W f_y \tag{7.11}$$

at the fire design situation as

$$R = W f_y k_y \tag{7.12}$$

where the reduction factor k_y is given by equations (7.5), (7.6) and (7.7).

Finally, the load effect E is given in both design situations as the bending moment at the mid-span point of the beam

$$E = (1/8)\,(G + Q)\,L^2 \tag{7.13}$$

In reliability analysis all basic variables are considered as random variables defined in Table 7.4. The fire load intensity q_f is described by the Gumbel distribution having the coefficient of variation 0,3 and the 80% fractile equal to the design value $q_{f,d}$=192,7 [MJ/m^2].

The corresponding mean μ_q of q_f is given as μ_q = 192,7/1,216 = 158,5 [MJ/m^2].

Basic variable X	Distribution	Characteristic value X_k	Design value in case of fire	Mean μ_X	Stand.dev. σ_X
$R = W f_y$- resistance[kNm]	Lognormal	294=1.251,2 ×235×10^{-3} (5%)	294	350,3=1.251, 2 ×280×10^{-3}	0,1 × μ_X [1)]
q_f - fire load [MJ/m^3]	Gumbel	192,7 (80%)	192,7	158,5	0,3 × μ_X
$b=(\rho c\lambda)^{0,5}$ [J/m^2 s$^{1/2}$ K]	Constant	1.160	1.160	1.160	0
$O = A_v \sqrt{h}/A_t$ [m$^{1/2}$]	Constant	0,04 m$^{1/2}$	0,04	0,040	0 [2)]
$A_{tf} = A_t / A_f$	Constant	4	4	4	0
G- perman. load [kN/m]	Normal	12 (50%)	12	12	0,1 × μ_X
Q-imposed load [kN/m]	Gumbel	9 (95%)	4,5	5,8	0,3 × μ_X
ξ_R-uncert. of R at 20°C	Normal	1 (50%)	1	1,0	0,1
ξ_R - uncert. of R in fire	Normal	1 (50%)	1	1,0	0,15
ξ_E - uncertainty of E	Normal	1 (50%)	1	1,0	0,1

Table 7.4. Review of basic variables.

Note on Table 7.4:

[1)] Recent research of available data concerning yield strength and geometrical data has indicated that the standard deviation could be less than $0,1 \times \mu_X$; this value is considered here as a safe assumption. 0,052 have also been considered in other parts of this document.

[2)] Opening factor is usually well known except the case when window glass brakes during the fire; then O may vary considerably (this is, however, not considered here).

Assuming the probabilistic models indicated in Table 7.4, the reliability of the simply supported beam has been analysed using the first order reliability method FORM and the program VAP [22]. It appears that at the persistent design situation the reliability index $\beta = 6,3$ ($\beta = 3,63$ for the original $W = 625,6$ cm^3 and $\beta = 4,5$ if in addition, ξ_R and ξ_E are assumed deterministic and equal to 1,0) is sufficiently high. At the fire design situation $\beta = 0,96$ (the conditional probability of failure $p_{f,fi}$ given the fire flashover is about 0,17). It is interesting to note that approximately the same reliability index $\beta = 0,96$ is obtained when the beam is designed for a given fire load intensity q_f (generally different from that determined by the above recalculation) using equations (7.3), (7.5), (7.6) and (7.7).

Table 7.5 shows the sensitivity factors α for all basic variables used in the example of a beam under fire design situation. Obviously, the fire load intensity q_f is the most sensitive basic variable, for which $\alpha_q = - 0,81$. If ξ_R and ξ_E are assumed deterministic and equal to 1,0, α_q becomes 0,902 as shown in Table 7.5. Thus, q_f is the dominating variable affecting the safety; this domination is even higher than the recommendation of in Eurocode 1 [17] to assume the weighting factor $\alpha_q \approx - 0,7$. It appears that reliability of the analysed beam may be well controlled by appropriate design value q_d of the fire load intensity q_f.

X	Characteristic	m	σ	V	Law	α	α ($\xi_R = \xi_E =$ deterministic = 1)
G	12	12	1,2	0,1	N	0,163	0,186
Q	9	5,8	1,73	0,3	G	0,229	0,268
R	294	350,3	35	0,1	LN	-0,244	-0,282
q_f	85	158,5	47,5	0,3	GL	0,808	0,902
ξ_R	1	1	0,15	0,15	N	-0,389	-
ξ_E	1	1	0,1	0,1	N	0,239	-

Table 7.5 Sensitivity factors α for basic variables of a beam under fire design situation.

It is interesting to note that approximately the same values sensitivity factors α, as those indicated in Table 7.5 are obtained when the beam is designed for another fire load intensity $q_{f,d}$ using equations (7.3), (7.5), (7.6) and (7.7).

7.4.1.4 Partial safety factor for fire load intensity

Design value $q_{d,f}$ of the fire load intensity q_f may be defined similarly as in the case of any action on the bases of the characteristic value q_k and partial factor γ_q using equation

$$q_{f,d} = \gamma_q \, q_{f,k} \tag{7.14}$$

If the fire load intensity q_f is described by Gumbel distribution and the characteristic value q_k is 80% fractile then in accordance with Eurocode recommendation (see 7.2.4) given in Eurocode 1 [17] the partial factor γ_q can be determined as

$$\gamma_q = \frac{q_{f,d}}{q_{f,k}} = \frac{\left(1 - v_q (0{,}45 + 0{,}78 \ln(-\ln(\Phi(\alpha\beta))))\right) \times 1{,}05}{1 - v_q (0{,}45 + 0{,}78 \ln(-\ln(0{,}8)))} \tag{7.15}$$

In this relationship Gumbel distribution having the coefficient of variation v_q is assumed for the fire load intensity q_f. The weighting factor α = 0,7; 0,9 and 1,0, the coefficient of variation v_q = 0,3 (see Table 7.5) are considered in this study.

The partial factor γ_q should be generally derived from the target probability $p_{t,fi}$ of a failure under fire design situation, which may be further derived from the overall target failure probability of failure p_t using the following simplified condition [18]

$$p_{fi} \times p_{t,fi} \leq p_t \tag{7.16}$$

Here p_{fi} denotes the probability of severe fire, which should be determined according to the values of the WG4 report.

Figure 7.8 shows a diagram of factor γ_q versus reliability index β obtained by reliability analysis and by approximation (7.15) recommended by Eurocode 1 [17]. Reliability analysis of the beam under fire design has been using programs VAP [22] and input data Table 7.4. The results shown in Figure 7.8 were derived assuming both a constant section modulus W (and considering variable characteristic value q_k [Procedure 1]) and a constant characteristic value q_k (and designing section modulus W using equation (7.3), (7.5) (7.6) and (7.7) [Procedure 2]). Thus, the results shown in Figure 7.8 are approximately valid for any characteristic value q_k as long as it is defined as 80% fractile of q_f. Both procedures lead to similar results.

Figure 7.8 shows that the γ_{qf} curve corresponding to α = -0,9 is a good approximation of the curve obtained by VAP calculations.

For the $\beta < 0$, the γ_{qf} curve corresponding to α = -0,9 is strongly on the safe side.

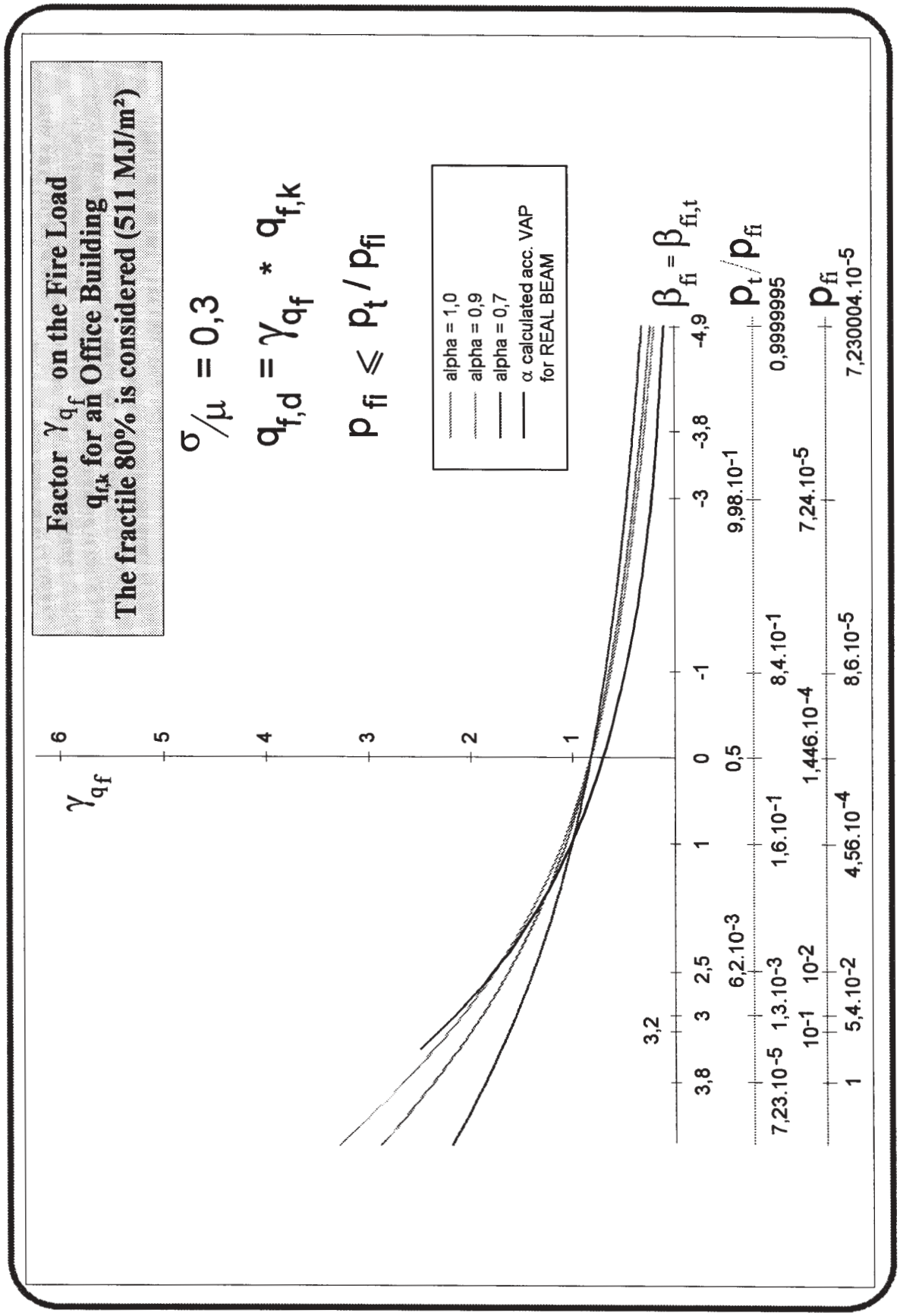


Figure 7.8

f:\fig_7_8N.ds4

7.5 CONCLUSION

The fire is considered as an accidental action. This accidental action can occur with a probability p_{acc} (also noted p_{fi} in other Chapters of this report) depending on the type of occupancy, on the fire compartment area and on the fire fighting active measures. The effect of the fire depends on some parameters. In buildings the most relevant parameter is the fire load.

The aim of the WG5 was to establish the methodology to provide the design value of the fire load which takes into account the fire probability. This design value is then used by the tool developed by WG1 (OZONE) to calculate the design natural fire curve.

In a first step, the Annex A of ENV 1991-1 [17], which describes the semi-probabilistic concept leading to the **design** values for the actions and for the materials properties, has been extended to the structural fire resistance in the following way.

The safety factors γ for the actions and the material properties has been deduced by a semi-probabilistic approach (Annex A of ENV 1991-1) which assumes implicitly that the failure probability of the structure p_f is lower than a target failure probability of $7{,}23.10^{-5}$ per working life of the building, which is equivalent to a safety factor β of 3,8 :

$$p_f \text{ (failure probability)} \leq p_t \text{ (target probability)} \qquad (7.17).$$

In case of fire, the main action is the fire which can be quantified by the fire load expressed in kg of wood or in MJ. However, this fire load becomes a real action for the structure only when there is a fire. The fire load influences really the structure only with a certain probability p_{acc}, p_{acc} being the product of p_1 (probability that a fire starts) and p_2 (probability that this starting fire turns to a flash-over or a fully engulfed fire compartment).

In case of fire which is considered as an accidental action the equation (7.17) becomes p_f (failure probability in case of fire) * p_{acc} (probability of fire) $\leq p_t$ (target probability). In that way the safety index β_{fi} has to be determined by using $p_{t,fi}$ which is equal to (p_t /p_{acc}) and enables us to determine the corresponding safety factor γ_{qf} for the fire load.

This factor has been divided into subcoefficients γ_{q1}, γ_{q2}, γ_{ni} to take into account the compartment size, the building type and the different active fire fighting measures like sprinklers.

The annex A of ENV 1991-1 [17] assumes also that the weighing factor α for the main action, here the fire load is equal to –0,7. The γ_{q1}, γ_{q2}, γ_{ni} defined in the Chapter 7.3.3 are based on this value of –0,7 for the weighing factor α_{qf} of the fire load.

In order to verify this assumption, reliability calculations described in Chapter 7.4 for different types of structure have been performed. These calculations show that the value of the weighing factor α_{qf} for the fire load is in fact closed to (-0,9).

The Figures 7.6 and 7.7 of the Chapter 7.3 becomes then the following Figures 7.9 and 7.10 which attest that the γ_{ni} can be even smaller than the ones deduced in Chapter 7.3 (Table 7.3). Moreover the VAP calculations [see Chapter 7.4.1 and Table D of Chapter 4.1 of the WG5 report (Book 2: Part 5) for unprotected steel beam, the Table 4.7 of the WG5 report (Book 2: Part 5) for unprotected steel column and Figures 4.10a and 4.14 of the WG5 report (Book 2: Part 5) for protected steel beam] prove that the γ_{ni} can even be reduced again.

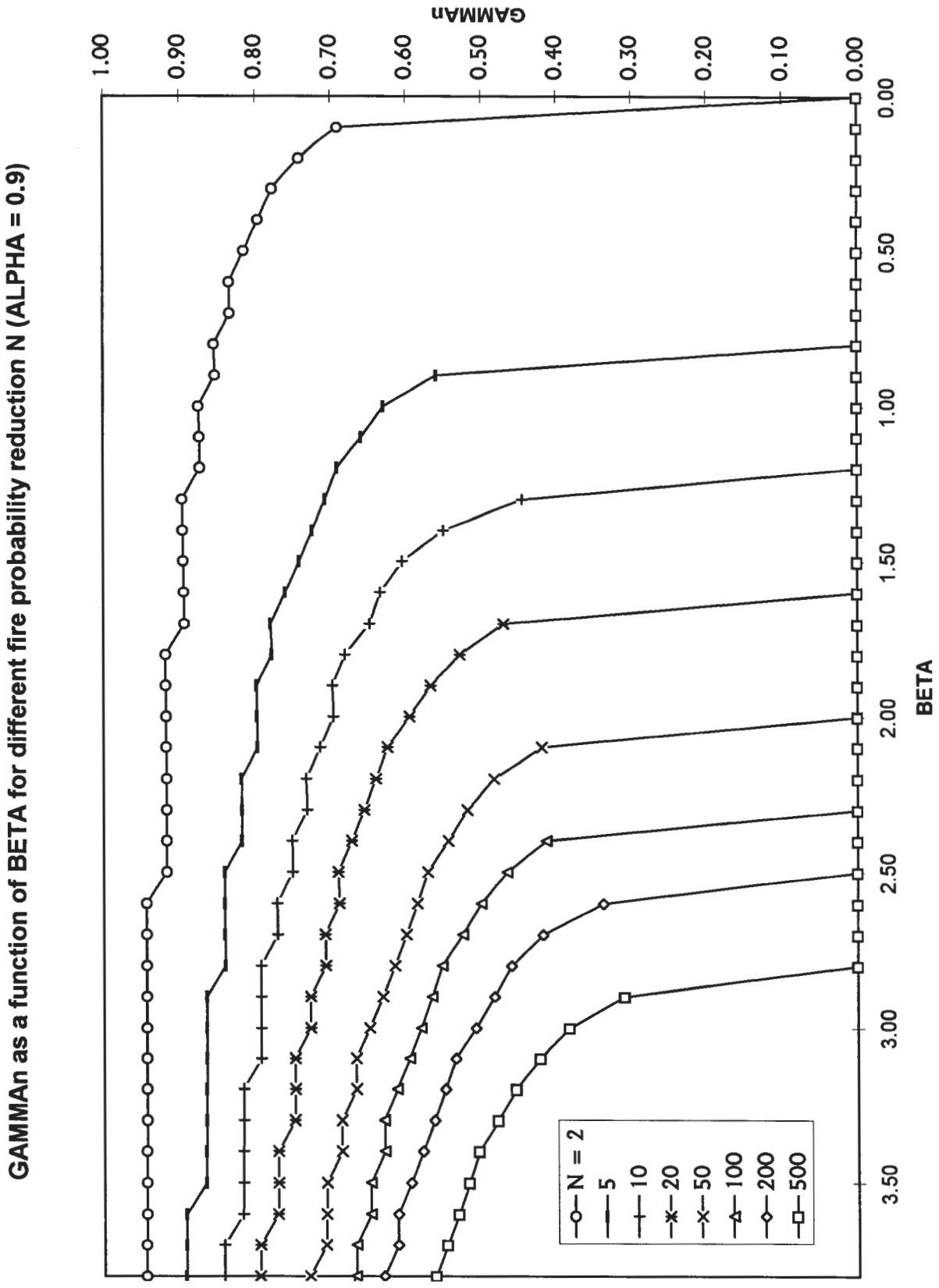

GAMMAn as a function of BETA for different fire probability reduction N (ALPHA = 0.9)
GAMMAn
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
BETA
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
N = 2
5
10
20
50
100
200
500

Figure 7.9

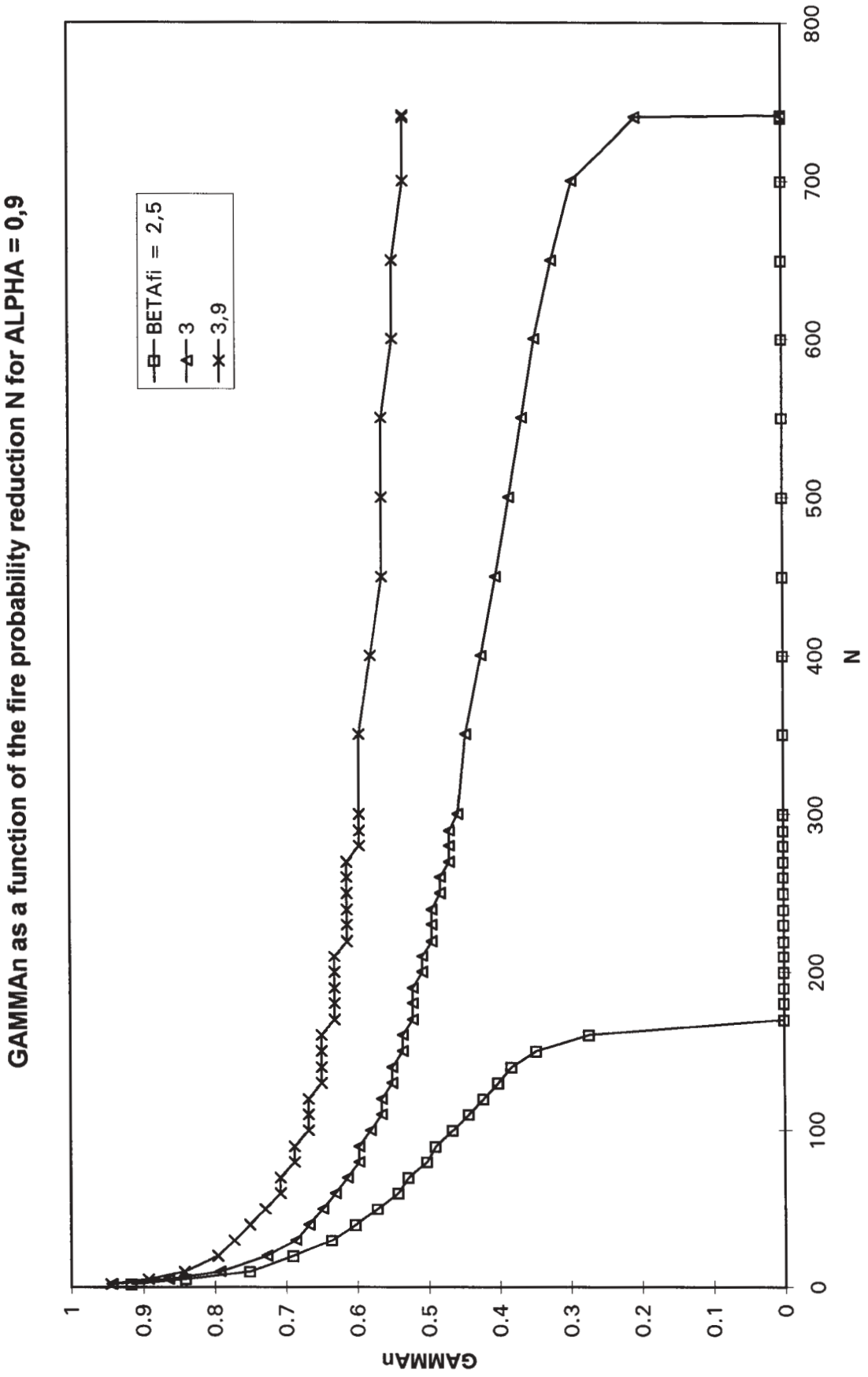

GAMMAn as a function of the fire probability reduction N for ALPHA = 0,9
BETAfi = 2,5
3
3,9
GAMMAn
N
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
100
200
300
400
500
600
700
800

Figure 7.10

All these calculations have been presented and discussed with the Advisory Committee (see Chapter 8). According to the WG5 report (Book 2: Part 5), to the comments of the Advisory Committee and to the works made in the scope of the ECSC project N°7215-PA/PB/PC-042 "Valorisation Project - Competitive Steel Buildings through Natural Fire Safety Concept", the factors γ_{q1}, γ_{q2}, γ_{ni} given in the Figures 7.11, 7.12 and 7.13 have been adopted.

Compartment floor area A_f [m²]	Danger of Fire Activation γ_{q1}
25	1,10
250	1,50
2500	1,90
5000	2,00
10000	2,13

Figure 7.11

Danger of Fire Activation γ_{q2}	Examples of Occupancies
0,78	artgallery, museum, swimming pool
1,00	residence, hotel, paper industry
1,22	manufactory for machinery & engines
1,44	chemical laboratory, painting workshop
1,66	manufactory of fireworks or paints

Figure 7.12

	Active Measures	Fully Developed FIRE PROBABILITY REDUCTION	γ_{ni}
Automatic Suppression	Sprinkler (S)	50	0,61
	Sprinkler + 1 independent Water Supply	100	0,53
Manual Fire Suppression	Work Fire Brigade (WFB)	50	0,61
	Standard Fire Brigade (SFB)	10	0,78
	... + Automatic fire detection by heat by smoke	... 4 ... 16	... 0,87 ... 0,73
	... + Automatic Alarm Transmission to Fire Brigade	... 4	... 0,87

Figure 7.13

By comparison with the effect of other active measures, with other Standards (SIA 81, ANPI, DIN, ENV 1991-2-2) and by discussions with the experts of the Advisory Committee, new factors γ_{ni} have been introduced to consider the independent water supplies in case of sprinklers and the normal fire fighting measures, which should be almost always present, such as the Safe Access Routes, the Fire Fighting Devices, and the Smoke Exhaust System in staircases. For these normal fire fighting measures, the γ_{ni} is 1,0 but becomes 1,5 if they have not been foreseen (see Figure 7.14).

Official Document		γ_{ni} Function of Active Fire Safety Measures										
		Automatic Fire Suppression		Automatic Fire Detection			Manual Fire Suppression					$\gamma_n^{min} = \gamma_{n1} \cdots \gamma_{n10}$ $\gamma_n^{max} = \gamma_{n4} \cdot \gamma_{n7}$
Title	Date of publication	Automatic Water Extinguishing System γ_{n1}	Independent Water Supplies 0 | 1 | 2 γ_{n2}	Automatic fire Detection & Alarm by Heat γ_{n3}	by Smoke γ_{n4}	Automatic Alarm Transmission to Fire Brigade γ_{n5}	Work Fire Brigade γ_{n6}	Off Site Fire Brigade γ_{n7}	Safe Access Routes γ_{n8}	Fire Fighting Devices γ_{n9}	Smoke Exhaust System γ_{n10}	
SIA 81	1984	0,50 / 0,59	/	0,83 or 0,69		0,83	0,67 or 0,63 $\gamma_{n6} \cdot \gamma_{n7} = 0,53$		/	1,0 / 1,39*	0,85	0,13 / 0,49
ANPI	1988	0,58 ⊙	1,0 | 0,86 | 0,65	0,82	0,68	included in ⊙	0,50	0,68	/	1,0 / 1,36*	/	0,07 / 0,48
DIN 18230-1	1987/98	0,60	/	0,90		/	0,60	/	/	/	/	0,32 / 0,54
ENV 1991-2-2	1995	0,60	/	/	/	/	/	/	/	/	/	0,60
NFSC PROPOSAL	1998	0,61	1,0 | 0,87 | 0,7	0,87 or 0,73		0,87	0,61 or 0,78		0,9 or 1 / 1,5*	1,0 / 1,5*	1,0 / 1,5*	0,15 / 0,57

Figure 7.14

* For normal fire fighting measures, which should be almost always present, such as the Safe Access Routes, the Fire Fighting Devices and the Smoke Exhaust System in staircases, the corresponding γ_{ni} should be taken as 1,5 in case those measures either are unsatisfactory either are not existing.

In short, the method to calculate the design fire load $q_{f,d}$ can be shared into two levels:

- **General Method (Level Two) : Calculation of $\gamma_{q,f}$**

For a compartment, it is possible to calculate the probability (noted p_{acc} or p_{fi} in this report) of a general fire (Fully Engulfed fire Compartment) depending on the fire compartment size, the type of occupancy and the active fire fighting measures by using the Tables 6.6 to 6.10 of Chapter 6).

Afterwards, the safety index β_{fi} depending on the target failure value p_t divided by the probability of a general fire, p_{acc} can be deduced.

$$\beta_{fi} = \phi^{-1}\left(\frac{p_t}{p_{acc}}\right) = \phi^{-1}\left(\frac{7{,}23.10^{-5}}{p_{acc}}\right)$$

with $p_{acc} = p_1 \cdot p_2 \cdot p_{n1} \cdots p_{ni}$,

p_{ni} being the failure probability of the active measure i

The curve VAP of the Figure 7.8 enables then to deduce the general factor γ_{qf} for the fire load.

- **Simplified Method (Level One) : Calculation of $\gamma_{q,f}$**

For a compartment, the Figures 7.11 to 7.14 enable to find the γ_{q1}, γ_{q2} and γ_{ni} . The factor γ_{qf} is equal to $\gamma_{q1} \cdot \gamma_{q2} \cdot \gamma_{n1} \ldots . \gamma_{ni}$.

- **Design fire load $q_{f,d}$**

When the factor γ_{qf} has been calculated by one of the two previous methods, the design fire load $q_{f,d}$ can be deduced :

$$q_{f,d} = q_{k,f} \cdot \gamma_{qf}$$

The design fire load is then used by the tool developed by WG1 (OZONE) to calculate the design natural fire curve. This natural fire curve obtained by using the design fire load is a realistic and probabilistic fire curve which defines the thermal action in order to design the structure with a sufficient safety.

8 ADVISORY COMMITTEE

The first meeting of the Advisory Committee has been held in London the 27th and 28th of June 1996. The second one in Esch/Alzette the 15th and 16th of January 97, the third one in Zürich the 20th and 21st of October 97, the fourth one in Erkelenz the 2nd, 3rd and 4th of June 98 and the last one in Esch/Alzette the 18th and 19th of January 99. Thanks to these meetings, the experts were able to give their comments and to guide the research in a satisfactory way for their point of view. The following members compose the Advisory Committee:

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9 THE NATURAL FIRE SAFETY CONCEPT (NFSC) APPLIED TO NEW BUILDINGS

This new concept has been applied to real projects

- Basket-Ball Hall in Pepinster (Belgium) – see **Annex 1**.
- Luxemburg Airport (Grand-Duchy of Luxemburg) – see **Annex 2**.
- Law Courts of Nantes (France) – see **Annex 3**.
- Building: Museum and Exhibition hall in URBINO (Italy) – see **Annex 4**.
- Office Building in Bilbao (Spain) – see **Annex 5**.
- Office Building "Langenthal", (Switzerland) – see **Annex 6**.
- Schools « Geesseknäppchen » in Luxemburg (Grand-Duchy of Luxemburg) – see **Annex 7**.

10 CONCLUSION

This research has established a new approach called the **N**atural **F**ire **S**afety **C**oncept (NFSC concept) to analyse the structural safety in case of fire. This NFSC procedure is more realistic and more credible because it takes account of active fire fighting measures and real fire characteristics.

This new concept should lead to both financial benefits and better safety guidance. Hence, examples of its use should become more numerous. Less money will be wasted in attempts to guarantee resistance of structures subjected, for instance, to two hours of a wholly unrealistic ISO (or ASTM) fire. Instead, it will be evident that it is much better to identify the active fire fighting measures that provide protection for people, such as detection, alarms, automatic alarm transmission to fire-fighters, smoke exhaust systems, and sprinklers.

If the safety of people is ensured in an optimal way, the structure itself can also benefit from those measures that aim to save occupants. Hence, the further costs needed to guarantee its stability in case of fire are strongly reduced and, in some cases, even reduced to zero.

The safety of the people has to be guaranteed. The objective may imply to limit the compartment size or to add some active fire fighting measures.
Concerning the fire resistance, the NFSC method can be applied following the next steps:

1. The first step consists in specifying the appropriate design fire scenarios. This means to define the fire characteristics (fire growth rate, rate of heat release, fire load) and the geometry of the fire compartment where the fire will be confined (size of the compartment, ventilation conditions, opening definition, glass breaking). The fire itself is represented by the Rate of Heat Release curve which is strongly depending on the characteristic fire load. For those parameters, design tables and design guidance are given in Chapter 5 and in the WG3 chapter of Book 2.

Occupancy	Fire Growth Rate	RHR_f [kW/m²]	Fire Load $q_{k,f}$ 80% fractile [MJ/m²]
Dwelling	Medium	250	948
Hospital (room)	Medium	250	280
Hotel (room)	Medium	250	377
Library	Fast	500	1824
Office	Medium	250	511
School	Medium	250	347
Shopping Centre	Fast	250	730
Theatre (movie/cinema)	Fast	500	365
Transport (public space)	Slow	250	122

Fire Growth Rate, Fire Loads and RHR_f for different buildings

2. Then the design fire load $q_{d,f}$ is calculated by multiplying the characteristic fire load $q_{f,k}$ by
    - m, the combustion factor equal by default to 0,8
    - γ_{q1}, taking into account of the fire compartment area
    - γ_{q2}, taking into account of the fire activation risk
    - γ_{ni}, taking into account of the different active fire fighting measures i (sprinkler, firemen, detection, automatic alarm transmission...). These active measures are generally imposed for life safety reason.
      (see the 3 tables on page 83 bis)

   This design fire load is used to determine the design Rate of Heat Release.

3. Afterwards the design natural fire curve is calculated by using the tools developed by the WG1 and considering the design rate of heat release as data.
4. The temperature field in the structure subjected to that design natural fire curve is then deduced by using the ENV 1993-1-2.
5. Knowing the temperature in the structure, the structural mechanical behaviour can be analysed either by using Eurocode 3 and 4 part1.2 for single elements or by using well-known thermo-mechanical software to simulate the whole structure. (For instance SAFIR in University of Liège, SISMEF and LENAS in CTICM, DIANA in TNO, CEFICOSS in ARBED...). The fire resistance time $t_{fi,d}^{nat}$ can then be deduced; this fire resistance time may often be infinite such that the structure is able to support the loads from the beginning to the end of the fire.
6. The safety of the structure is verified by comparing the fire resistance time $t_{fi,d}^{nat}$ with the required time depending of the evacuation time and the consequences of the failure.

This NFSC approach which consists of calculating the structure subjected to a natural fire curve taking into account the active fire fighting measures enables to design the structure against a more realistic action and therefore to optimise the safety. Moreover this natural fire safety concept enables to make the trade-off between active and passive fire protection in a scientific and practical way. Practical way because this safety quantification is based on the procedure already used now by the structure engineers for normal design at room temperature. The method has only been extended to the structural design in case of fire.

Compartment floor area A_f [m²]	Danger of Fire Activation γ_{q1}
25	1,10
250	1,50
2500	1,90
5000	2,00
10000	2,13

Danger of Fire Activation γ_{q2}	Examples of Occupancies
0,78	artgallery, museum, swimming pool
1,00	residence, hotel, paper industry
1,22	manufactory for machinery & engines
1,44	chemical laboratory, painting workshop
1,66	manufactory of fireworks or paints

Official Document	γ_{ni} Function of Active Fire Safety Measures										$\gamma_n^{min} =$ $\gamma_{n1} \cdots \gamma_{n10}$ $\gamma_n^{max} = \gamma_{n4} \cdot \gamma_{n7}$
	Automatic Fire Suppression		Automatic Fire Detection			Manual Fire Suppression					
Title	Automatic Water Extinguishing System γ_{n1}	Independent Water Supplies 0 | 1 | 2 γ_{n2}	Automatic fire Detection & Alarm by Heat γ_{n3}	Automatic fire Detection & Alarm by Smoke γ_{n4}	Automatic Alarm Transmission to Fire Brigade γ_{n5}	Work Fire Brigade γ_{n6}	Off Site Fire Brigade γ_{n7}	Safe Access Routes γ_{n8}	Fire Fighting Devices γ_{n9}	Smoke Exhaust System γ_{n10}	
NFSC PROPOSAL	0,61	1,0 | 0,87 | 0,7	0,87 or 0,73		0,87	0,61 or 0,78		0,9 or 1 / 1,5*	1,0 / 1,5*	1,0 / 1,5*	0,15 / 0,57

* For normal fire fighting measures, which should be almost always present, such as the Safe Access Routes, the Fire Fighting Devices and the Smoke Exhaust System in staircases, the corresponding γ_{ni} should be taken as 1,5 in case those measures either are unsatisfactory either are not existing.

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12 LIST OF NOTATIONS

Notations to be used in the NFSC research
(mainly based on Eurocode notations)

Indices

a identifies data about steel
c convective component of heat transfer
cr critical value
d design value
f related to the floor area A_f
fi identifies values relevant for fire design
i related to the element " i "
k characteristic value
r radiative component of heat transfer
t related to the total area A_t
w identifies data about windows

Latin case letters

A_{cei} = ceiling area of the fire compartment [m^2] = **D . W**
A_f = floor area of the fire compartment [m^2] = **D . W**
A_{fi} fire area
A_s = H * *(fire compart. perimeter)* = surrounding wall area of the fire compartment [m^2]
A_t = $A_s + A_f + A_{cei}$ = total area of enclosure (walls, ceiling and floor, including openings)
A_T total area of floor, ceiling and wall, minus total area of the window [m^2]
A_w **$A_w = \Sigma A_{wi} = A_{wh} + A_{wv} = \Sigma A_{whi} + \Sigma A_{wvi}$ = sum of window area [m^2]**
A_{wh} = $\Sigma (h_i . w_i)$ = total area of horizontal openings [m^2]
A_{whi} area of horizontal opening " i " [m^2]
A_{wi} area of window " i " [m^2]
A_{wv} total area of vertical openings [m^2]
A_{wvi} area of vertical opening " i " [m^2]
c specific heat of boundary of enclosure [J/kgK]
c_i specific heat of layer i
D **depth of the fire compartment [m]**
g acceleration due to the gravity [m/s^2]
h_a = $\Sigma A_{wvi} . h_i / A_{wv}$ = weighted average of window heights on all walls [m]
h_i **height of window "i" [m]**
$h_{net,r}$ radiative heat flux component per unit surface area [W/m^2]
$h_{net,c}$ convective heat flux component per unit surface area [W/m^2]
$h_{net,d}$ = $\gamma_{n,c} . h_{net,c} + \gamma_{n,r} . h_{net,r}$ = net heat flux due to convection and radiation [W/m^2]

H **height of the fire compartment [m]**

H_{uo} net calorific value of dry materials

H_{ui} net calorific value [MJ/kg]

k_b conversion factor for thermal properties of the fire compartment enclosure according to (4) of Annex E.

L $= A_f \cdot q_f =$ fire load [kg of wood] or [MJ]

m_i optional factor describing the combustion behaviour of the material " i "

$M_{k,i}$ amount of combustible material " i " [kg]

O opening factor : $A_w (h_a)^{1/2} / A_t$

q_d $= \gamma_q \cdot \gamma_n \cdot q_k$ = design fire load density

$q_{f,d}$ design value of the fire load density related to the surface area A_f of the floor [MJ/m²]

$q_{t,d}$ design value of the fire load density related to the surface area A_t of the enclosure whereby $q_{t,d} = q_{fd} \cdot A_f / A_t$ [MJ/m²]

R rate of burning [kg of wood/s] or [W]

s_i thickness of layer i

$t_{e,d}$ $= q_{f,d} \cdot k_b \cdot w_f$ = equivalent time of fire exposure [min]

t_{fi} standard fire resistance (property of the member or structure) [min]

$t_{fi,requ}^{Nat}$ required natural fire resistance period [min]

$t_{fi,requ}$ required standard fire resistance time (nominal value) [min]

T_{am} ambient temperature (=293) [K]

T_f fire temperature [K]

T_o flame temperature at the window [K]

u moisture content in % by weight

w sum of window widths on all walls ($w = \Sigma w_i$) [m]

w_E ventilation factor according to (5) of Annex E

w_i **width of window " i " [m]**

W **width of the fire compartment [m]**

Greek upper case letters

Φ configuration factor [-]

Θ temperature [°C] ; Θ [°C] = T [K] - 273

Θ_a steel temperature

Θ_{cr} critical temperature [°C], relevant for steel

Θ_r radiation temperature of the environment of the member [°C]

Θ_g gas temperature in fire exposure [°C]

Θ_m surface temperature of the member [°C]

Θ_o initial gas temperature [°C]

Greek lower case letters

α coefficient of heat transfer [W/m² K]

α_v $= A_v / A_f$ = area of vertical openings A_v in the facade related to the floor area of the compartment where the limit $0{,}025 \leq \alpha_v \leq 0{,}25$ should be observed

α_h $= A_h / A_f$ = area of horizontal openings A_h in the roof related to the floor area of the compartment

γ partial safety factor [-]

γ_q safety factor depending on the consequences of failure and frequency of fires, according to national specifications $(q_d = \gamma_q \cdot \gamma_n \cdot q_k)$

γ_n differentiation factor accounting for active fire protection measures (if not considered in the fire model) - according to national specifications; for approved fire extinguishing systems γ_n = [0,6] may be used $(q_d = \gamma_q \cdot \gamma_n \cdot q_k)$

$\gamma_{n,c}$ factor to account for different national types of test and equals [1,0] $(h_{net,d} = \gamma_{n,c} \cdot h_{net,c} + \gamma_{n,r} \cdot h_{net,r})$

$\gamma_{n,r}$ is equal to [1,0] as $\gamma_{n,c}$ $(h_{net,d} = \gamma_{n,c} \cdot h_{net,c} + \gamma_{n,r} \cdot h_{net,r})$

ε_f emissivity related to fire compartment, usually taken as [0,8]

ε_m emissivity related to surface material; where the fire design Parts of ENV 1992 to 1996 and ENV 1999 give no specific data, ε_m should be used as [0,7]

ε_{res} $= \varepsilon_f \cdot \varepsilon_m$ = resultant emissivity [-]

η $= A_T/(A_w h^{1/2})$ [$m^{-1/2}$] in Annex C

λ thermal conductivity of boundary of enclosure [W/m K]

λ_i thermal conductivity of layer i

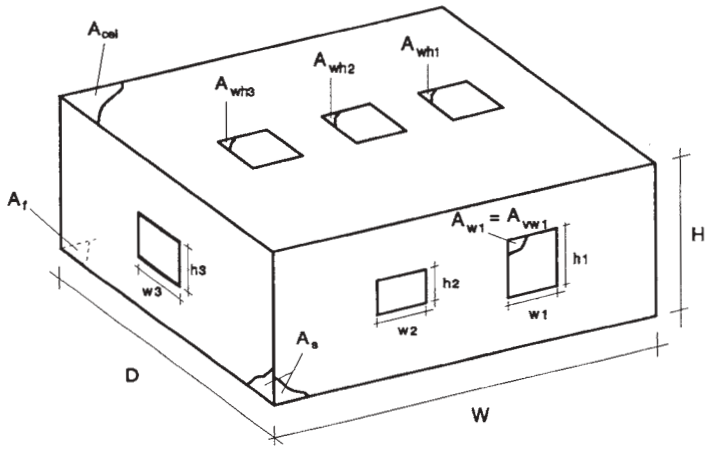
ρ density of boundary of enclosure [kg/m³]

τ_F free burning fire duration (assumed to be 1200) [s]

ψ load combination coefficients

ψ_C $L/(A_w \cdot A_T)^{1/2}$ [kg of wood/m²] in Annex C

$\psi_{i,D}$ optional factor for assessing protected fire loads in Annex D



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ANNEXES

THE NATURAL FIRE SAFETY CONCEPT APPLIED TO REAL BUILDINGS

ANNEX 1. Basket-Ball Hall in Pepinster (Belgium)

ANNEX 2. New Airport Terminal Luxembourg (PA-RE)

ANNEX 3. Law Courts of Nantes (France)

ANNEX 4. The Observatory of the City in the Ancient Ducal Stable in URBINO (Italy)

ANNEX 5. Office Building in Madrid, (Spain)

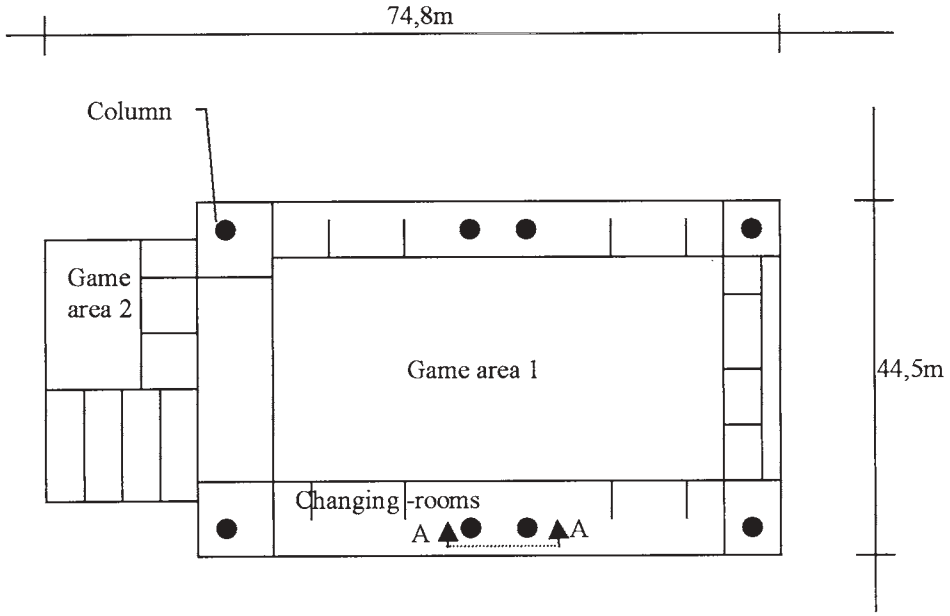
ANNEX 6. Office Building "Langenthal", (Switzerland)

ANNEX 7. Complex «Geesseknäppchen», Lycée (Lot L), (Luxemburg)

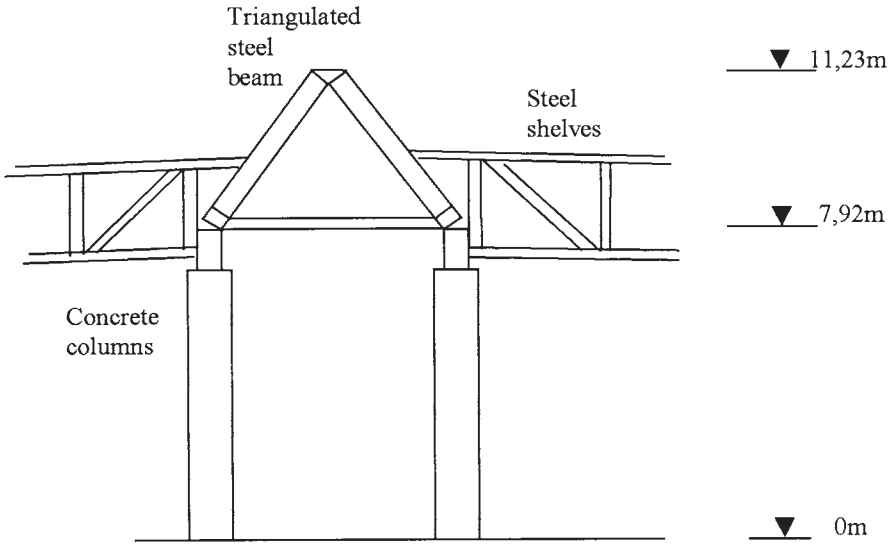
ANNEX 1

1 BASKET-BALL HALL IN PEPINSTER, BELGIUM

A new basket-ball hall for a famous club has been built in Belgium. All the permission of the authorities have been obtained to redo the fire design of this building with the natural fire safety concept.



Schematic view of the first level of the hall



A-A elevation view

Figure 1.1 : Structure of the hall

The roof is made of steel shelves. One triangulated steel beam in Λ (see Figure 1.1) is 44 m long. First, a cold design has been made. The Belgian regulations require the beam to stand 30 minutes of ISO fire. The calculation has shown that a measure was necessary. The first solution was to put an insulating painting on the beam. This measure multiplies the price of the beam by two (compared to the cold design). The other solution was to use a bigger section of the beam (over design). This solution has been adopted because the price was only multiplied by 1,40. A design using the natural fire safety concept developed in this research has been done and, among other things, has enabled to reduce the increase of the price of the beam ([9] of chapter 10 of the main part).

ANNEX 2

2 NEW AIRPORT TERMINAL LUXEMBOURG

2.1 OBJECT

The new terminal building at the airport Luxembourg shall be built in a distance of 20 m north-east of the existing building on an area of about 60 m x 90 m. It extends to four floors:

- one engineering floor;
- one Tarmac-floor on the apron plain;
- one ground floor (which borders on the land side on the existing ground level);
- Mezzanine-level in the air space above the ground floor.

An architecturally striking shell in conjunction with a shed-glazing forms the roof closing.

The supporting structure for the area ground floor and Mezzanine is intended as composite steel construction, the roof structure in unprotected steel structure. The use can be described as arrival terminal with appropriate luggage belts in the ground floor, lounges, connecting and waiting zones on the Mezzanine-level.

Furthermore, office rooms for the airport administration and several companies are placed in the Mezzanine area.

One has to note regarding the building heights, that the Mezzanine level is situated about 4,80 m over ground floor level, the roof structure about 12,50 m at the lowest point, respectively 18 m at the highest point, over ground floor level.

2.2 FIRE LOADS IN TERMINAL BUILDINGS

In order to find out fire loads in terminal buildings, an extensive survey according to the procedure DIN 18230 for the airport building in Köln-Bonn (Germany) exists. The investigations for separate function unit's show in the enclosed table the following essential knowledge and results:

1. The fire load, which is related to the area, is very different: large-surface areas show a low fire load, small-surface areas show a high fire load; there are typical point fire loads.

2. The calculated fire load can be classified in the following groups: minimum fire loading less than about 25 - 35 kWh/m² (90-126 MJ/m²) for the wide area spaces; 200 - 300 kWh/m² (720-1.080 MJ/m²) for the point fire loadings.

3. The point fire loadings maximally extend on areas of 100 - 150 m².

Bereich	Terminal	Brandlast [kWh]	Fläche [m²]	Brand-belastung [kWh/m²]	Haupt-brandlast
SEC-Control/Passkontrolle	R	2.415	82	29	GFK-Polyester
Lufthansa-Lounge	R	5.410	63	86	Holz
Ausbau A	R	2.140	145	15	PKW
Lufthansa-Check In	R	20.353	169	120	GFK-Polyester
Büro Lufthansa	R	2.617	35	75	Holz, Papier
Lufthansa Senator-Lounge	R	9.006	297	30	Holz, Leder
Wartezone	R	1.789	121	15	Holz, PA
Deutsche Bank	R	10.208	115	89	Holz, Papier
Reisebüro Atlas Reisen	R	4.309	14	308	Holz, Papier
Reisebüro l' tur	R	267	14	262	Holz, Papier
Reisebüro Portugalia	R	3.144	14	225	Holz, Papier
Euro Lloyd Reisebüro	R	3.173	14	227	Holz, Papier
Reisebüro Air France	R	3.909	14	279	Holz, Papier
Reisebüro Hungarian Airl.	R	3.144	14	225	Holz, Papier
Reisebüro Alitalia	R	3.144	14	225	Holz, Papier
Hapag Lloyd Reisebüro	R	8.607	28	307	Holz, Papier
Wartezone	R	1.108	18	62	Holz, PA
Reisebüro Lufthansa	R	11.223	70	160	Holz, Papier
Wartezone (Stern B)	M/R	2.271	600	4	PKW
Reisebüro Luftbrücke	M/R	1.581	14	113	Holz
Reisebüro Istanbul Airl.	M/R	1.415	14	101	Holz
Reisebüro Tjaereborg	M/R	2.765	14	198	Holz, Papier
Reisebüro Aeroflot	M/R	2.376	14	170	Holz, Papier
Reisebüro LOT	M/R	2.376	14	170	Holz, Papier
Discount Travel/First	M/R	6.990	28	250	Holz, Papier
Coffee Shop Bonn	M/R	8.887	287	31	PE, Holz
Wartezone	M/R	690	30	23	GFK-Polyester
Büchershop	M/R	14.897	42	355	Papier
Phono/Foto/Souvenirs	M/R	4.343	42	103	Holz, PE
Reisebüro ITS-Service	M/R	6.027	26	232	Holz, Papier
Wartezone	M/R	1.455	84	17	Holz, PA
Lederwaren/Parfümerie	M/R	6.783	42	162	PE, PA
Shop Tabakwaren	M/R	1.179	14	84	Holz, Papier
Shop Süsswaren	M/R	2.718	16	170	Holz, Zucker

Wartezone	M/L	748	30	25	GFK-Polyester
Bar Kolonia	M/L	10.131	44	230	Holz
Alpha Reisebüro	M/L	3.213	14	230	Holz, Papier
AHS Reisebüro	M/L	2.655	14	190	Holz, Papier
LTU Reisebüro	M/L	2.538	14	181	Holz, Papier
Reisebüro Ogden Aviation	M/L	3.091	14	221	Holz, Papier
British Airw./Deutsche BA	M/L	4.432	28	158	Holz, Papier
Wartezone (Stern C)	M/L	7.646	600	13	PE, PKW
Reisebüro Fischer Reisen	M/L	1.988	14	142	Holz, Papier
Reisebüro alltours	M/L	1.941	14	139	Holz, Papier
Abfertigung D	L	37.390	8.030	5	Holz

2.3 FIRE SAFETY CONCEPT

A fire safety concept was developed for the overall object, whose essential content shall be described in the following sample.

The installation of a sprinkler installation as active fire safety facility will be necessary for all areas which are covered by the Mezzanine as well as all rooms and areas on the Mezzanine level, which have got an intermediate ceiling closing.

A sprinkler arrangement directly below the roof area of the hall will not be necessary.

The floor ground is separated from the lower level by a fireproof slab.

Exclusively not combustible building materials are used for the overall building.

The escape and rescue routes will be secured by a system of exits which lead directly outside or into stairwell, that led outside. They can be reached in a distance of maximally 40 m of each point of the object.

The width is interpreted according to the regulations of Luxembourg for 1.980 people in the floor ground, respectively and 700 people on the Mezzanine level.

A system of organisational-internal measures (person responsible for fire safety, fire brigade plans, fire safety rules, etc.) has been established considering the global aspect of fire safety, but will not be more detailed afterwards.

2.4 DEFINITION OF FIRE SCENARIOS

Fire scenarios, which are described hereafter and have to defined in the starting phase of the calculation, form the basis for the calculated fire simulation. Since the use of a zone-model is planned for the calculation, the fire scenario can be essentially defined by rate of heat release and fire area. While one has to investigate the smouldering fire scenarios for the calculation of the dimensions for the smoke and heat venting, you have to suppose the evaluation of representative till extensive fire scenarios, which are on the safe side, for the determination of the thermal loading of the supporting structure.

Scenario 1

One assumes a rate of heat release of 5 MW on a fire area of 10 m^2 in a sprinklered area according to literary information as representative fire of a shop area (e. g. duty-free) in the ground floor.

Scenario 2

A rate of heat release of 8 MW on a 5 m^2 fire area for duration of 10 minutes is assumed in order to investigate the effect of a liquid fire.

Scenario 3

One has to calculate with a maximum release of energy till 20 MW. This was related to a (consciously reduced) fire area of 20 m^2 for duration of one hour in order to sham a consciously effective fire event.

Consequently, this very conservative estimation disregards the existence of a sprinkler installation extensively.

Scenario 4

A very high-energy, extensive fire with a rate of heat release of 50 MW for the duration of one hour shall be investigated as limit consideration. Consequently, this scenario disregards the existence of a sprinkler installation and describes, with this, the extreme case, that the sprinkler installation in the case of a fire would fail.

Again, the size of fire was reduced in order to show in the calculation at the same time the temperature effect on the building components in direct nearness of the fire.

The RHR curves for the 4 scenarii are given on Figure 2.4

2.5 CALCULATION BY SINGLE ROOM-MODEL

The temperatures of the hot gas were first realised in using a single room-model. The dimensions of the compartment were registered with an area of 5.400 m^2, the building height with 10 m and describe, with this, the geometry, which results above the Mezzanine level till the beginning of the roof structure. On this occasion, the ventilation conditions were investigated in using the above-mentioned smoke and heat venting installation and the scenarios were investigated in the prescribed case differentiation.

The orientation calculations showed and demonstrated a strong influence of the building height, which is described in the following diagram as summary of 12 computer proceedings (see Figure 2.1).

Virtual room heights of 3, 5, 8 as well as 10 m for the different fire capacity, respectively heat releases according to the above-mentioned description, were evaluated.

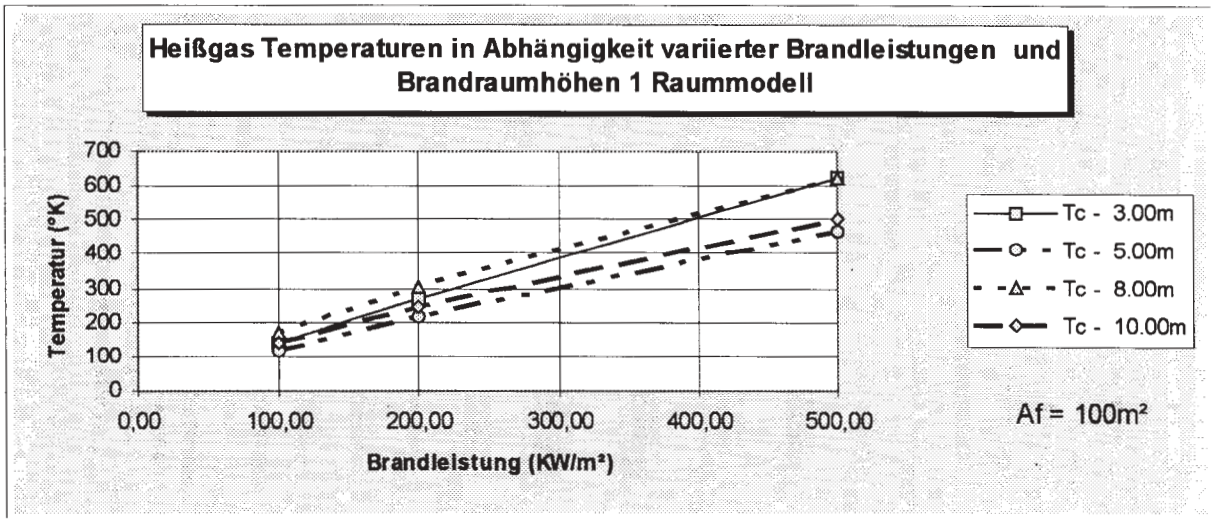


Figure 2.1: Gas temperature as a function of the fire load for different room heights in case of a 5400 m² compartment.

The compartment size is reduced to 900 m² in further calculations, which corresponds to 1/6 of the overall area, in order to register the fire event closer and exacter in the local area of the seat of fire.

The temperature evaluations - again in dependence on the changeably assessed height - are shown in the following Figure 2.2 as result of 12 further computer proceedings.

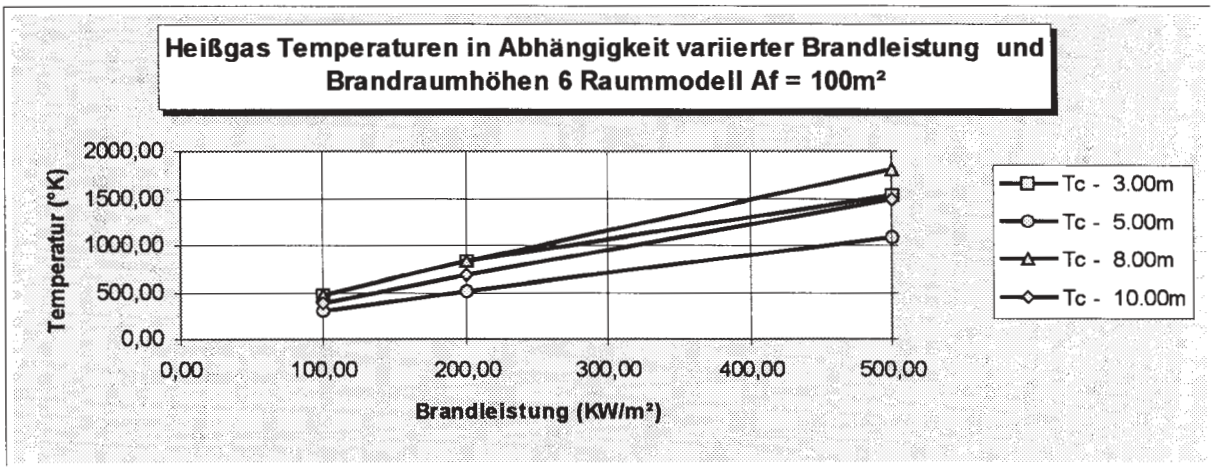


Figure 2.2: Gas temperature as a function of the fire load for different room heights in case of a 900 m² compartment.

The results demonstrate very well, that, especially as a result of the large building height respectively room height, a clear reduction of the hot gas temperatures is proved.

In a comparison between single room-model and six rooms-model, higher local temperatures were resulted in the field of the factors 2 till 3, which one has to expect in view of the geometry conditions.

2.6 EVALUATION WITH A TWO-ZONE-MULTI-COMPARTMENT MODEL

Similar calculations have been made by using the Software ARGOS which is a Two-Zone-Multi-Compartment Model.

The hall of the Airport Terminal has been divided into several fictive compartments (1, 2, 5 compartments) as shown on Figure 2.3. In each case, the fire is localized on the mezzanine, in the centre of the Air Terminal (see Figure 2.3 of chapter 2 of the Main Part).

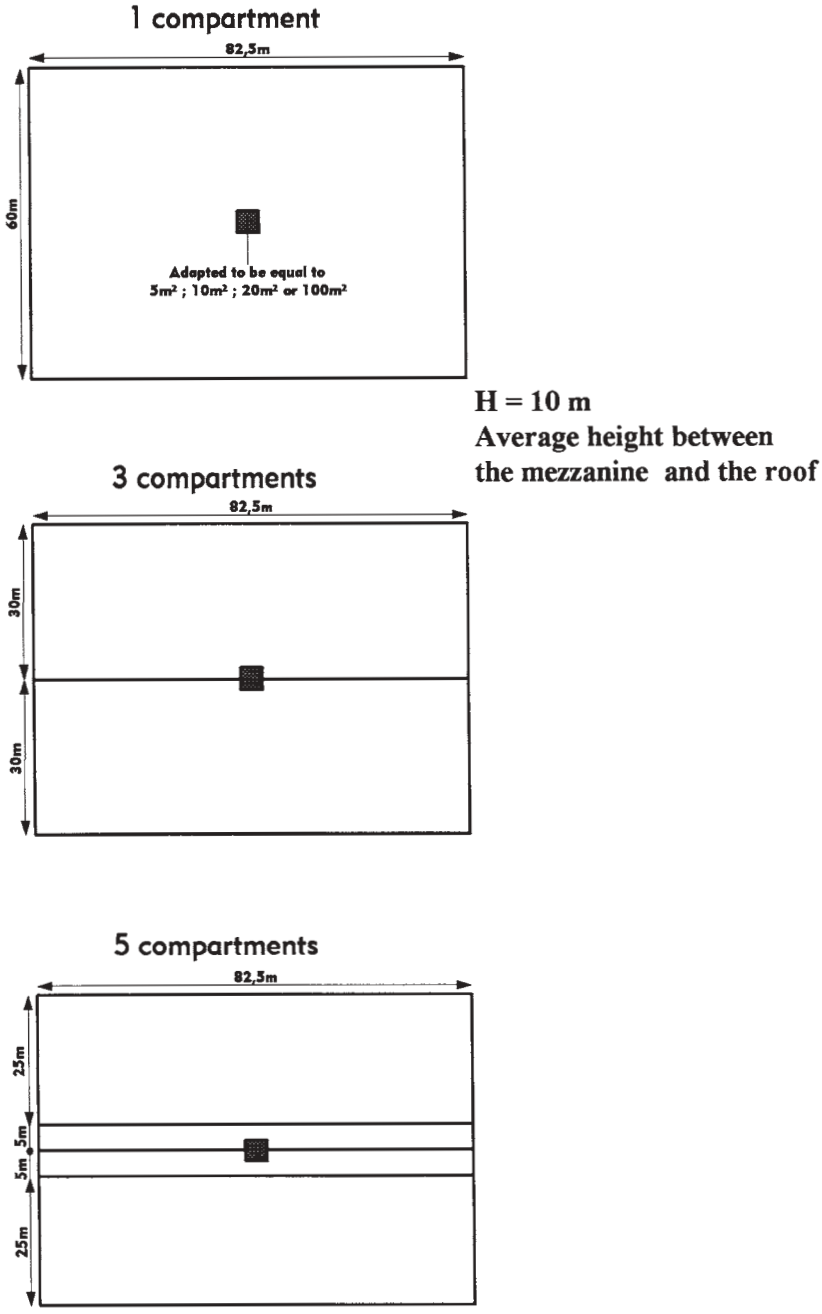


Figure 2.3: 3 ARGOS simulations: division of the fire compartments into sub-compartments (1, 3 and 5 sub-compartments)

The height of the free zone and the temperature of the smoke layer are given in the following diagrams (see Figures 2.4 to 2.8).

The Figure 2.4 shows the RHR Curves for the 4 scenarii:

Scenario 1: 5 MW
Scenario 2: 8 MW
Scenario 3: 20 MW
Scenario 4: 50 MW

The Figure 2.5 shows the height of the free zone (without smoke) for the 4 scenarii (ARGOS simulation with only 1 compartment).

The Figure 2.6 shows the temperature of the smoke layer for the 4 scenarii (ARGOS simulation with only 1 compartment).

The Figure 2.7 shows the height of the free zone (without smoke) for the 4 scenarii (ARGOS simulation with 5 compartments).

The Figure 2.8 shows the temperature of the smoke layer for the 4 scenarii (ARGOS simulation with 5 compartments).

The temperature fields provided by the ARGOS simulations have to be combined with the TEFINAF calculations taking into account the localized peak of temperature above the fire (see Figures 2.9 to 2.14). That procedure has been developed in the scope of the ECSC Research 7210 - SA 210/317/517/619/932 and is described in the WG1 report.

The Figure 2.9 (scenario 1) shows the temperature of the steel as a function of the time for different radial distances (TEFINAF calculation).

The Figure 2.10 (scenario 1) shows the temperature of the steel as a function of radial distances for different times (TEFINAF calculation).

The Figure 2.11 (scenario 2) shows the temperature of the steel as a function of the time for different radial distances (TEFINAF calculation).

The Figure 2.12 (scenario 2) shows the temperature of the steel as a function of radial distances for different times (TEFINAF calculation).

The Figure 2.13 (scenario 3) shows the temperature of the steel as a function of the time for different radial distances (TEFINAF calculation).

The Figure 2.14 (scenario 3) shows the temperature of the steel as a function of radial distances for different times (TEFINAF calculation).

The summary of results (ARGOS and TEFINAF) is given on Figure 2.15. On this table are also shown the results of the NBN S21-208 which is a simplified method giving the air temperature of the smoke layer.

These temperature fields, corresponding to the 4 scenarii, have enabled to justify an unprotected steel structure for the roof.

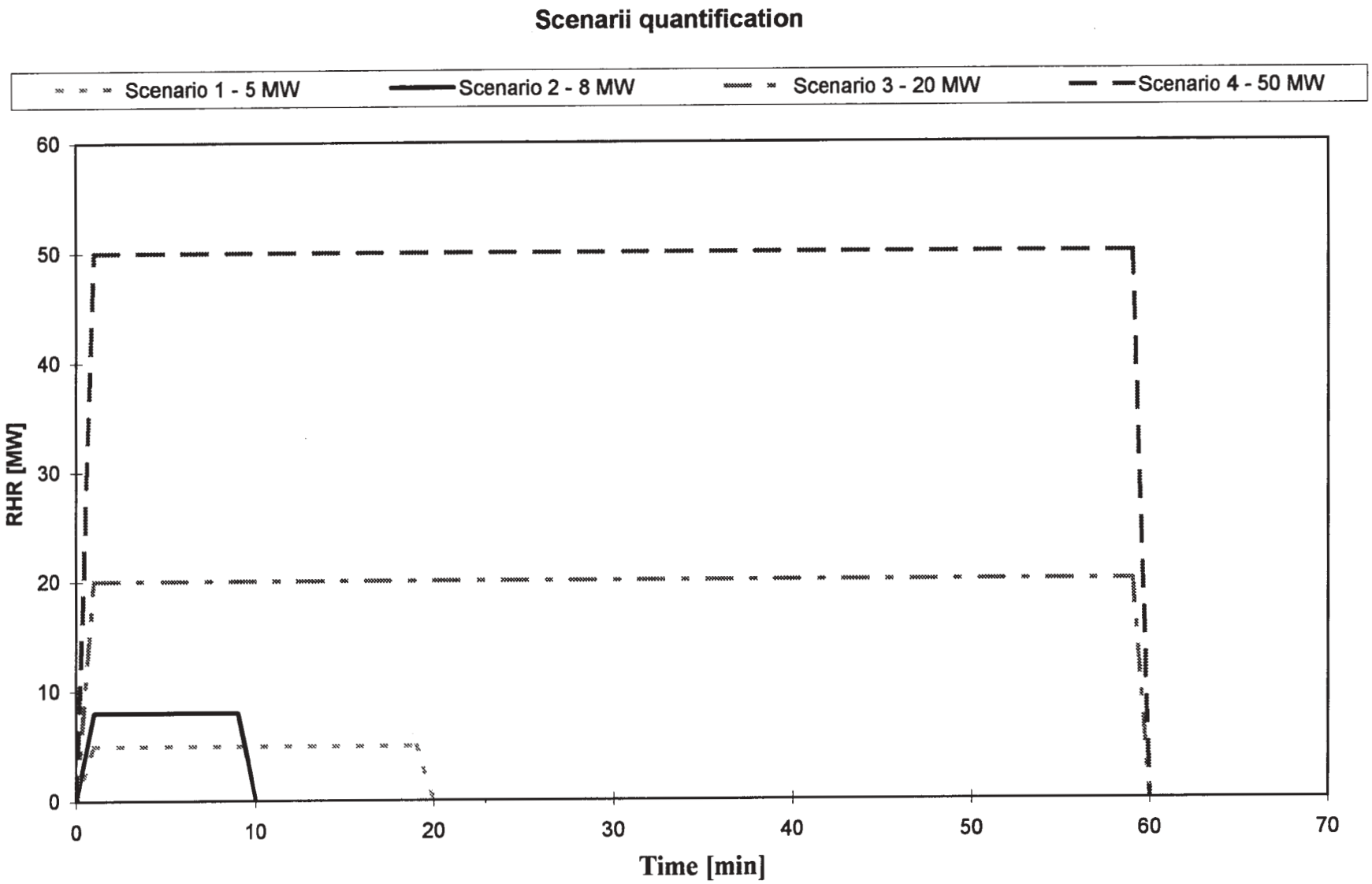


Figure 2.4: RHR Curves for the 4 scenarii.

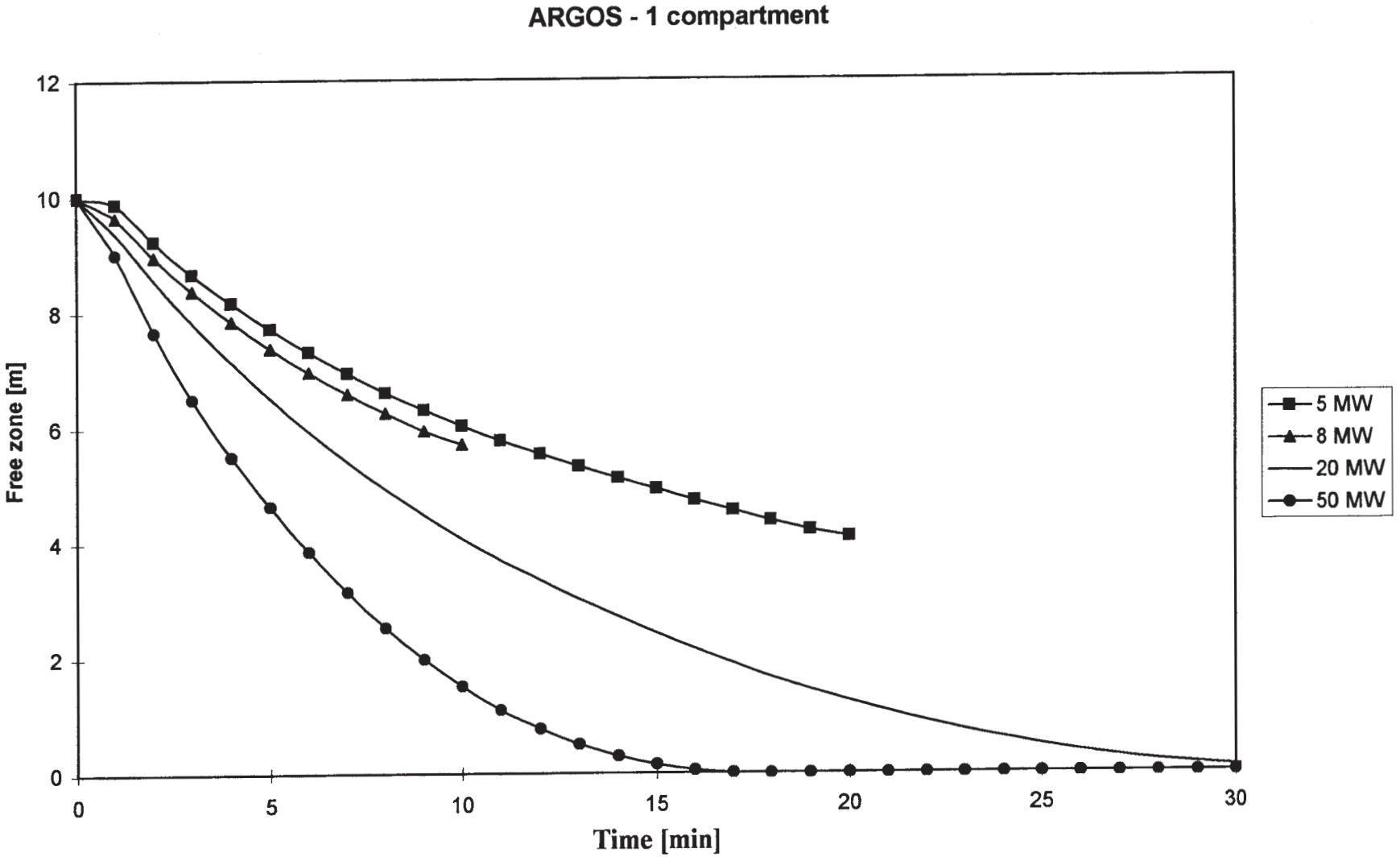


Figure 2.5: ARGOS simulation with only 1 compartment - Height of the free zone (without smoke) for the 4 scenarii.

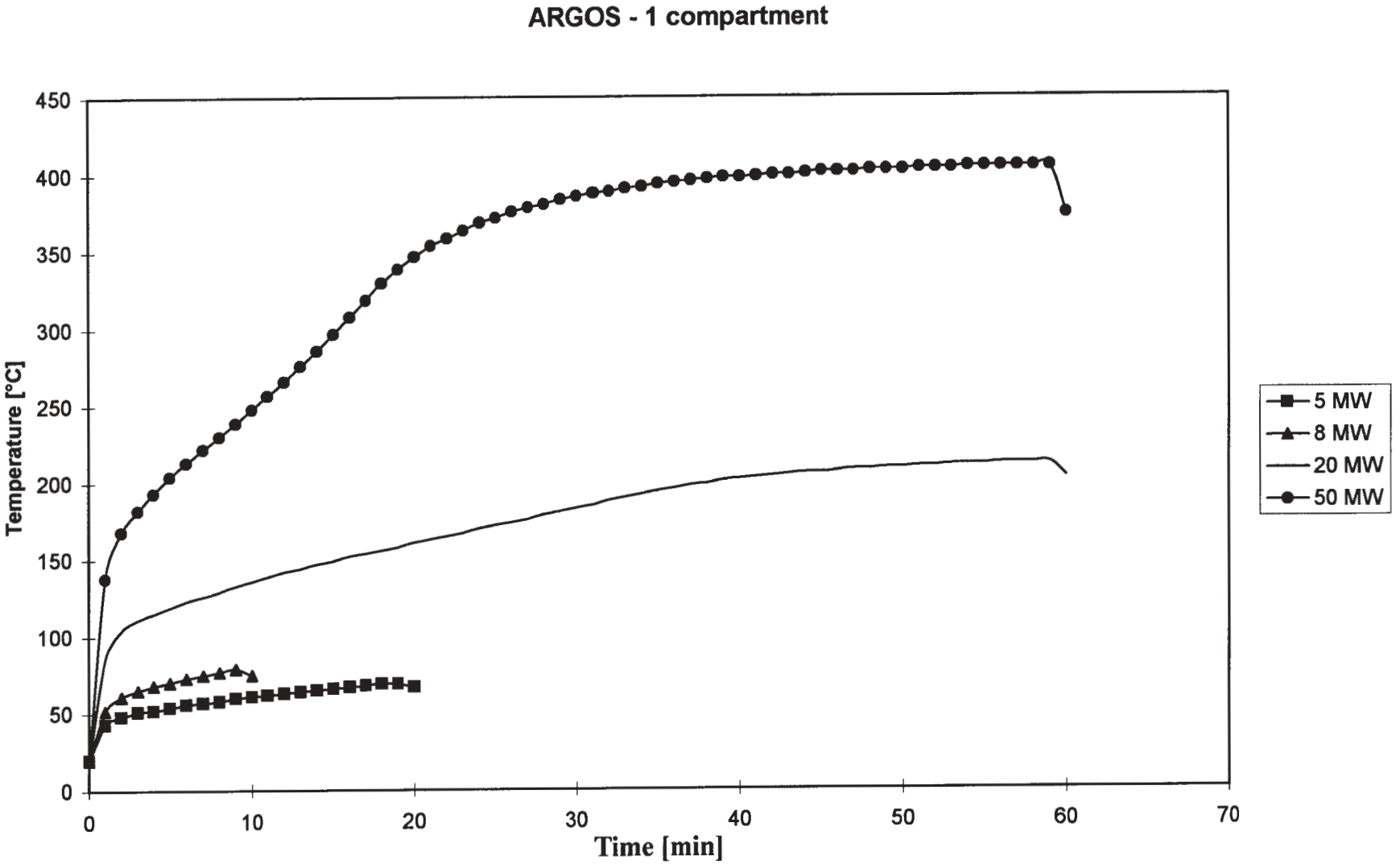


Figure 2.6: ARGOS simulation with only 1 compartment - Temperature of the smoke layer for the 4 scenarii.

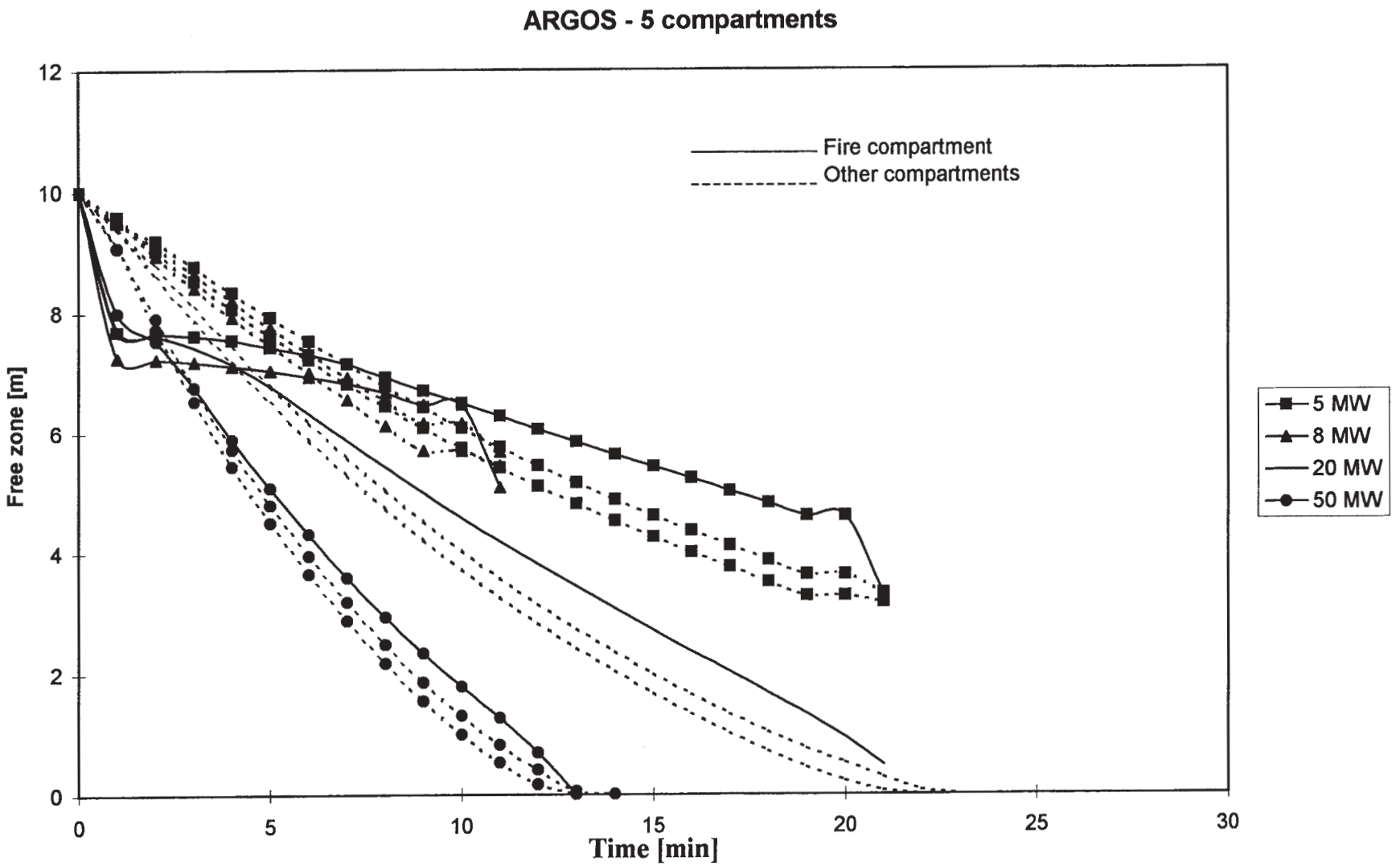


Figure 2.7: ARGOS simulation with 5 compartments - Height of the free zone (without smoke) for the 4 scenarii.

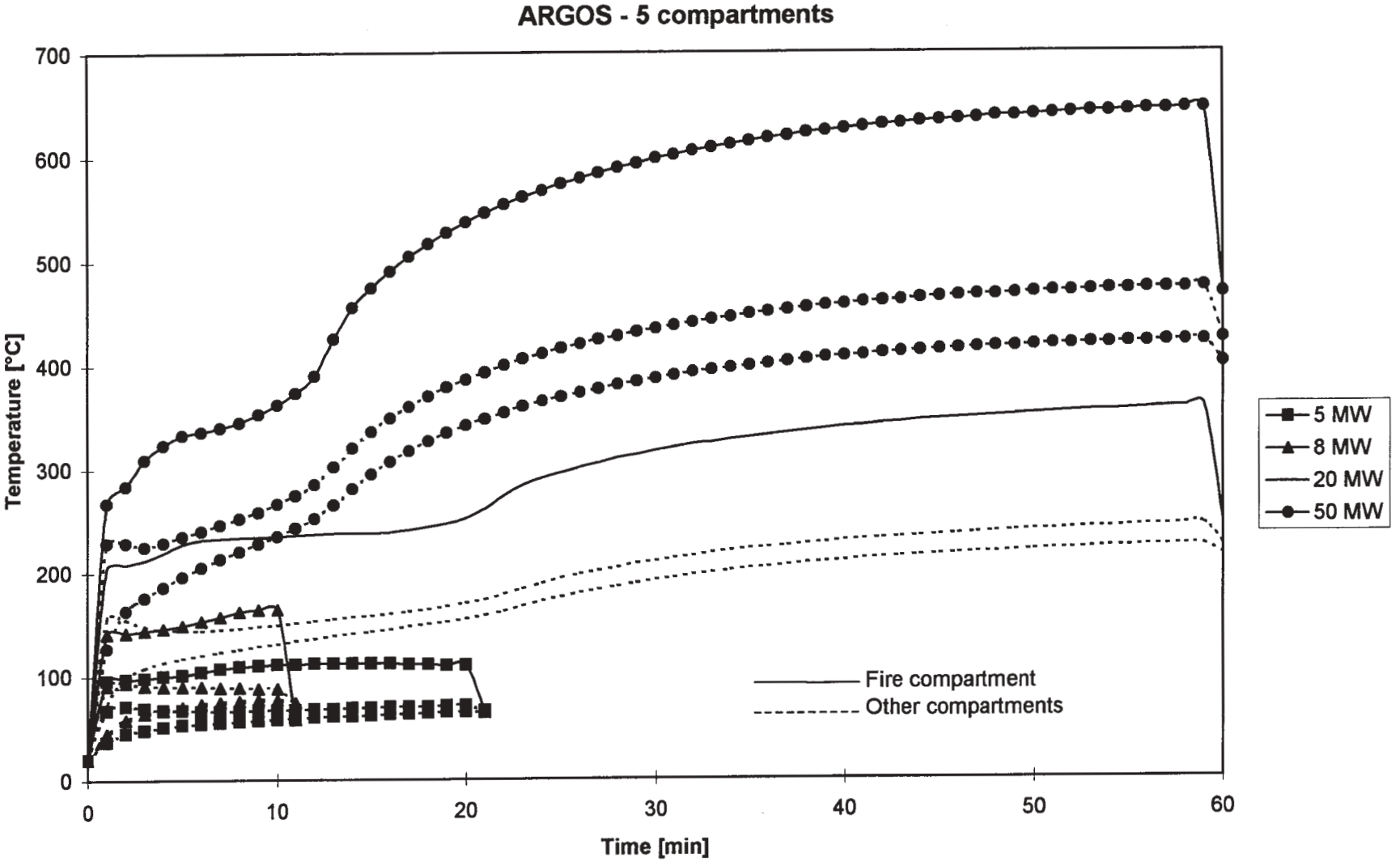


Figure 2.8: ARGOS simulation with 5 compartments - Temperature of the smoke layer for the 4 scenarii.

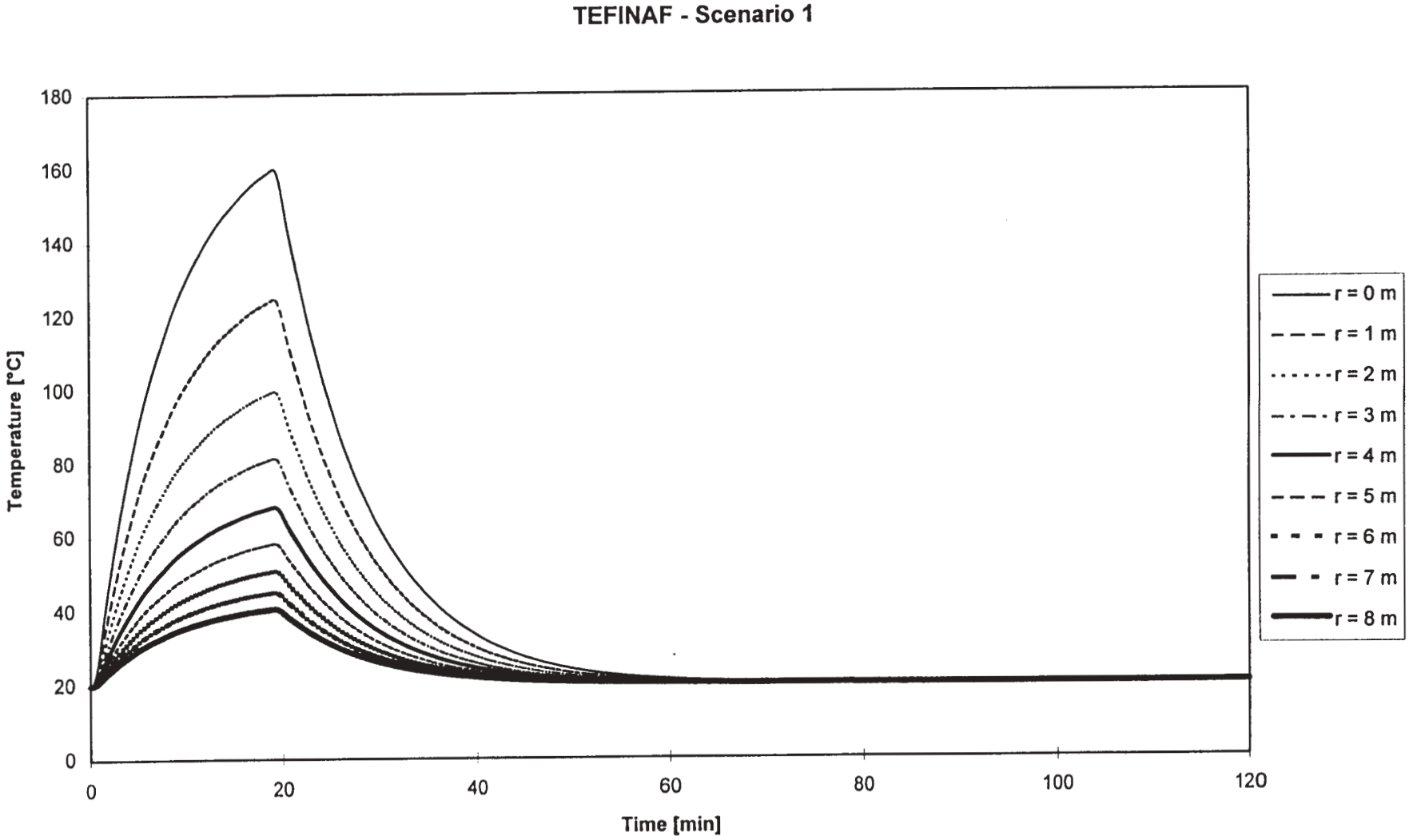


Figure 2.9: TEFINAF calculation – (scenario 1)
Temperature of the steel as a function of the time for different radial distances

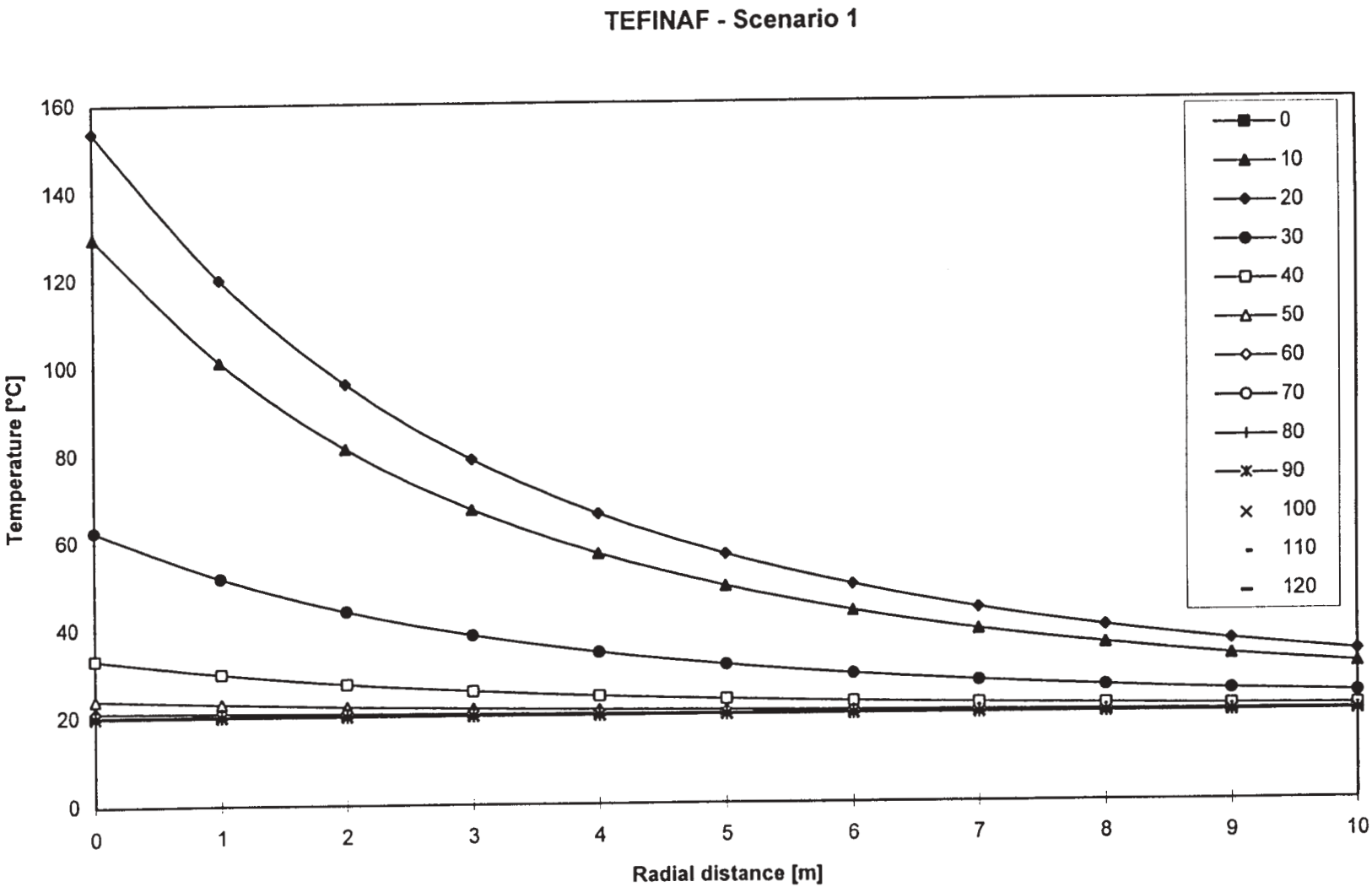


Figure 2.10: TEFINAF calculation – (scenario 1)
Temperature of the steel as a function of the radial distance for different times

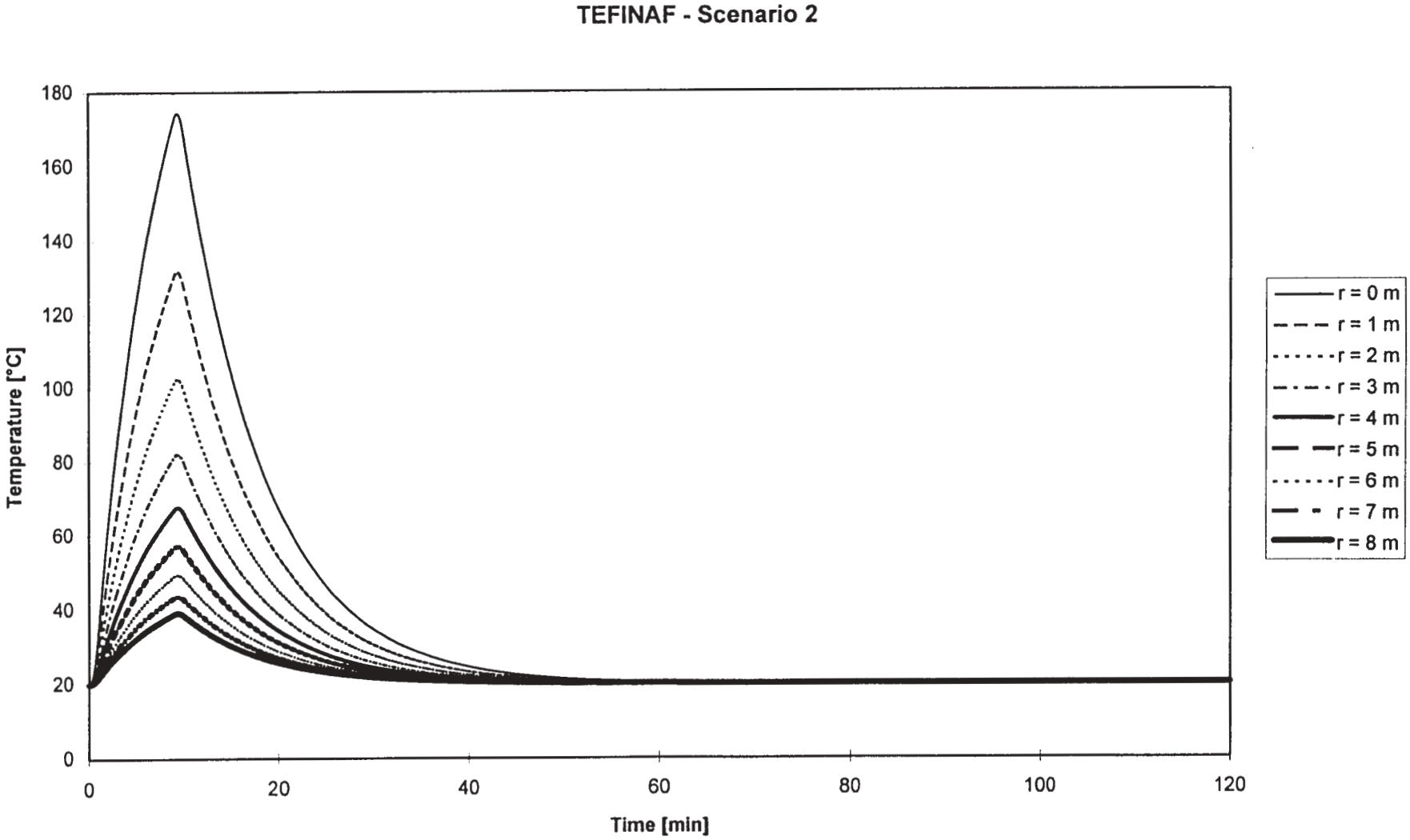


Figure 2.11: TEFINAF calculation – (scenario 2)
Temperature of the steel as a function of the time for different radial distances

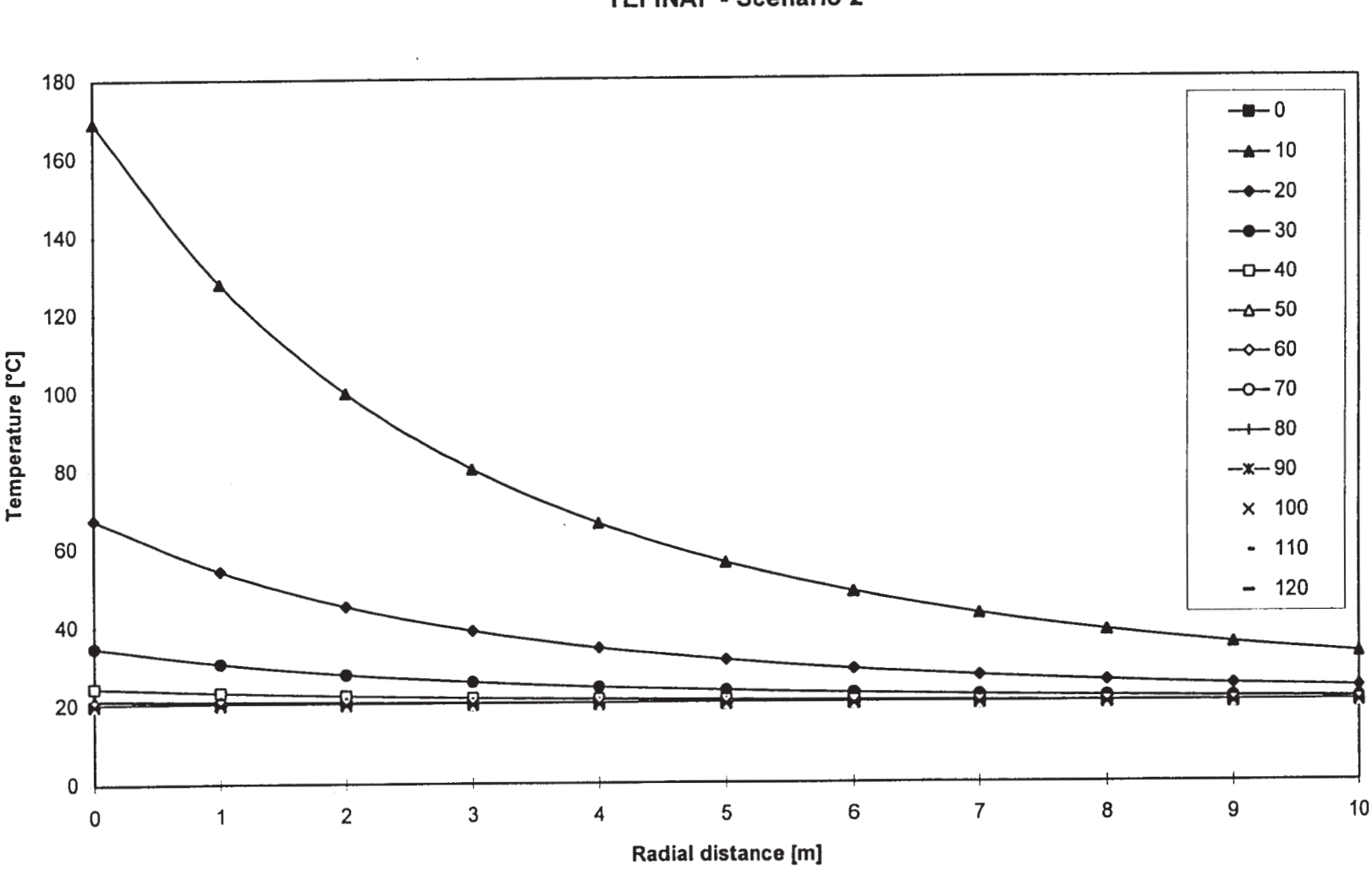


Figure 2.12: TEFINAF calculation – (scenario 2)
Temperature of the steel as a function of the radial distance for different times

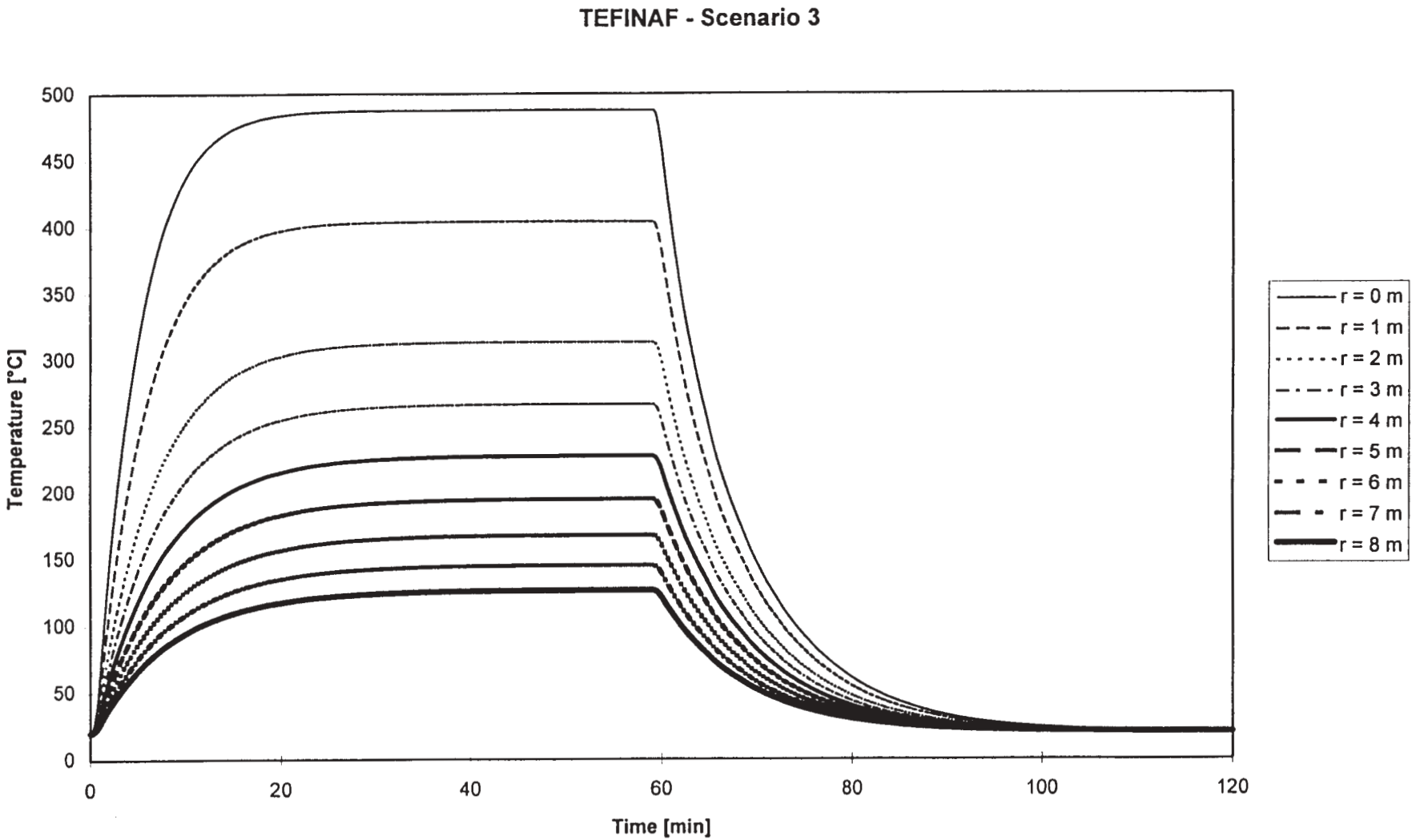


Figure 2.13: TEFINAF calculation – (scenario 3)
Temperature of the steel as a function of the time for different radial distances

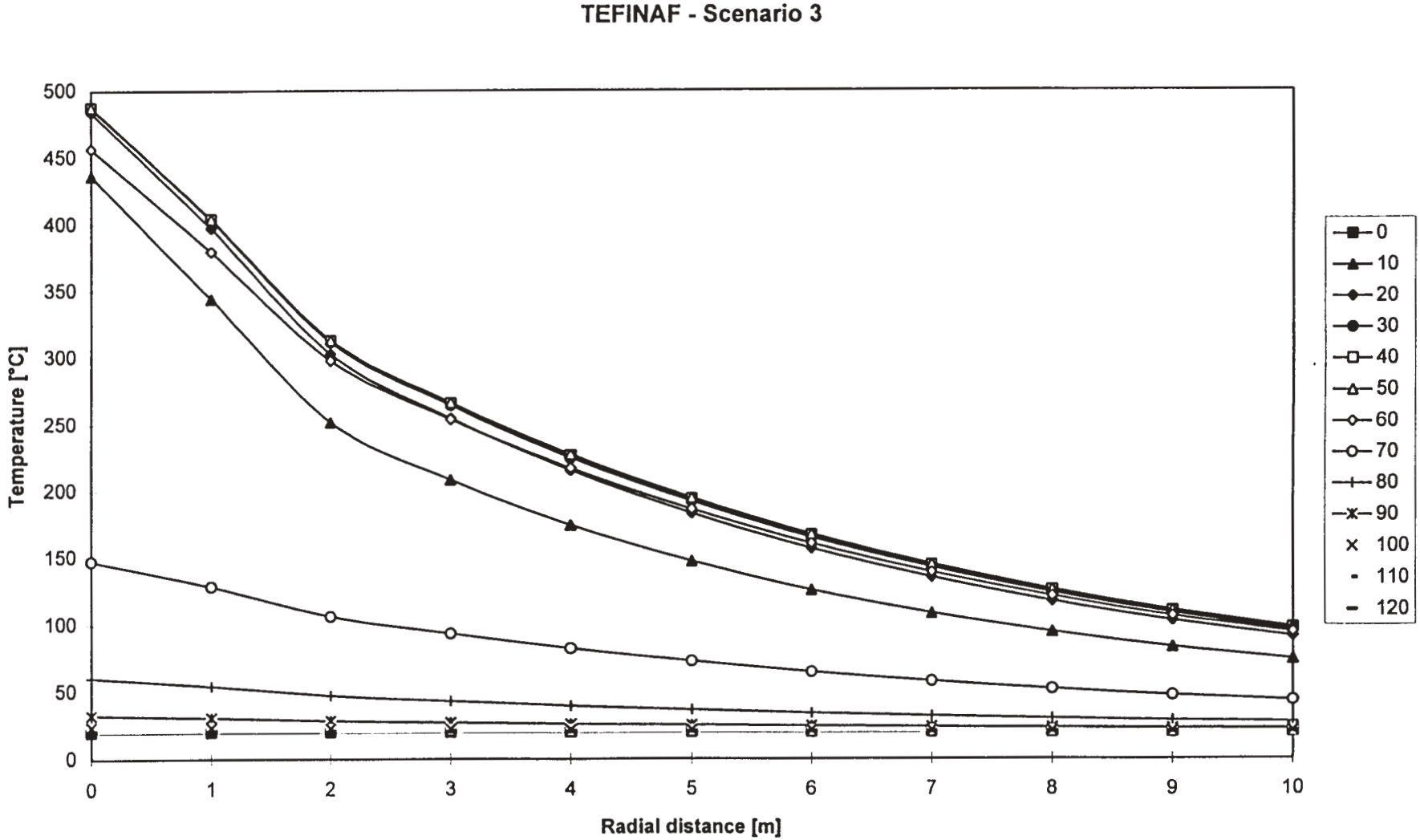


Figure 2.14: TEFINAF calculation – (scenario 3)
Temperature of the steel as a function of the radial distance for different times

		Maximum Temperature [°C]			
		ARGOS Air temperature		TEFINAF Steel temperature of an IPE 200	NBN Air temperature
		H =8 m	H=10 m		
Scenario 1 5 MW	**1 compartment**	73	69	**160**	**71**
	3 compartments	141	109		
	5 compartments	146	112		
Scenario 2 8 MW	**1 compartment**	85	79	**175**	**138**
	3 compartments	201	162		
	5 compartments	206	164		
Scenario 3 20 MW	**1 compartment**	215	212	**488**	**175**
	3 compartments	374	337		
	5 compartments	405	359		
Scenario 4 50 MW	**1 compartment**	409	405	**618**	**226**
	3 compartments	654	598		
	5 compartments	724	646		

Figure 2.15: Summary of results: ARGOS - TEFINAF - NBN

result.drw

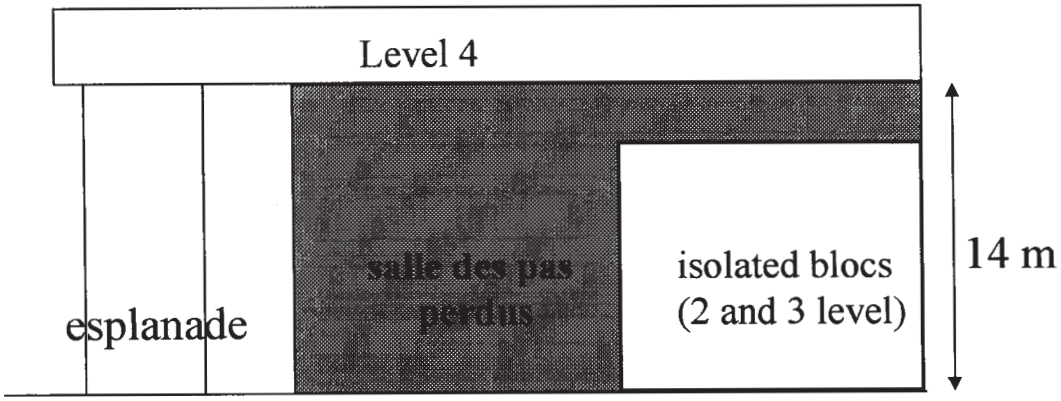
3 LAW COURTS OF NANTES, FRANCE

3.1 INTRODUCTION

3.1.1 The building

The Palais de Justice de Nantes is in construction from January 1998 to July 1999. It is composed on two main levels:

- Level 1: the 'Salle des pas perdus' with dimensions of about 6.000 m^2 and an height of about 10 m, in which 3 structurally independent blocks are built. These blocks with three levels for 'salles d'audience' and offices are bounded by 90 minutes ISO-fire rating walls.
- Level 4: a surface of 9.000 m^2 divided in 9 fire-compartments.



3.1.2 The structure

The structure is defined by steel columns of 10 m high and large steel trusses for beams of the level 4.

The particularity of such structure is that the lower beams of the trusses are in the large volume of the level 1 ("Salle des pas perdus").

3.1.3 The requirements

According to the French regulation ([7] of chapter 3.4 of this annex 3.1), the trusses have to satisfy a fire stability of 90 minutes according to the standard fire.

90 minutes are also required for the columns and for the slab between the level 1 and the level 4.

3.2 NATURAL FIRE SAFETY CONCEPT APPLICATION

3.2.1 Introduction

The large volume of the level 1 contains a small fire load. The compartmentation of the level 2 and 3 generates a well-defined scenario of their contribution to the fire resistance of the steel structure in the large volume of the level 1.

According to such configuration, the structural behaviour of the steel structure existing in the level 1 can be determined from a natural fire safety concept.

In order to do it, the following four phases have been defined:

- fire scenarios definition
- fire development assessment
- calculations of heat transfer to structural elements
- determination of the structural behaviour

The main assumption of this study considers that the compartmentation with an ISO-fire rating is sufficient in case of natural fire.

3.2.2 Fire scenarios

Different fire scenarios have been defined according to the possible fire source that may induce heat transfer to the steel structure.

The different sources come from 3 rooms:

- 'salle d'audience' at the level 2,
- offices of the level 3,
- 'salle des pas perdus' of the level 1.

From these 3 fire sources, 8 fire scenarios have been defined [2] :

A. fully engulfed fire in the 'salle d'audience' without glass break
B. fire in an office at the level 3 near the out door
C. fully engulfed fire in the 'salle des pas perdus'
D. localised fire in the salle des pas perdus
E. localised fire around a column
F. fully engulfed fire in the salle des pas perdus for external columns
G. fully engulfed fire in the 'salle d'audience' with glass break

3.2.3 Fire development

A more detailed description of the fire development calculations is given in reference [5].

3.2.3.1 Scenario A

A description of the furniture of the 'salle d'audience' has been given. An estimation of about a high fire load density of 68 kg of wood/m^2 has been deduced.

Coming from this fire load density and the dimension of the room and of the openings (doors), the temperature-time curve in the room has been determined using the code CFAST and is shown in Figure 3.1. A comparison with the standard curve may be observed in the figure.

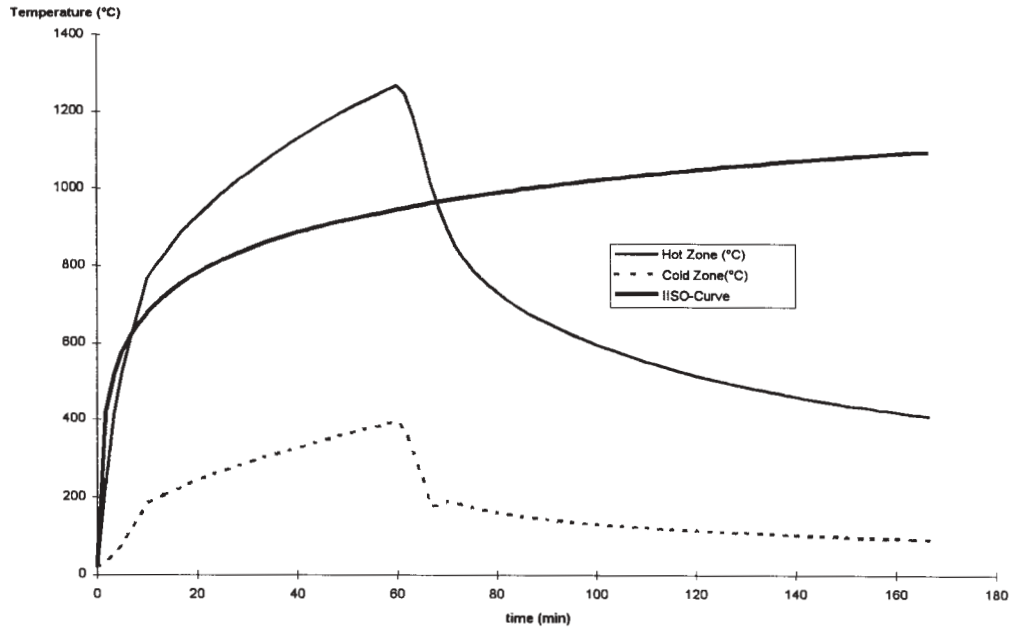


Figure 3.1: Temperature in the 'salle d'audience d'assises'

3.2.3.2 Scenario B

In such case it was decided that a fire development in the level 3 might heat the structure by the smoke evacuation through the outside door. So a scenario considering a fire development in level 3 with propagation between rooms and smoke movement to outside is studied. The Figure 3.2 shows the description of the rooms used for the simulations.

It was assumed that the fire density of the offices is 17 kg/m2. Four openings exist: window of the office 1 to outside, and doors from office 1 to corridor, office 2 to corridor, and corridor to outside.

The Figure 3.3 shows the temperature of the upper layer in each room, considering fire stability of the walls and of the partitions.

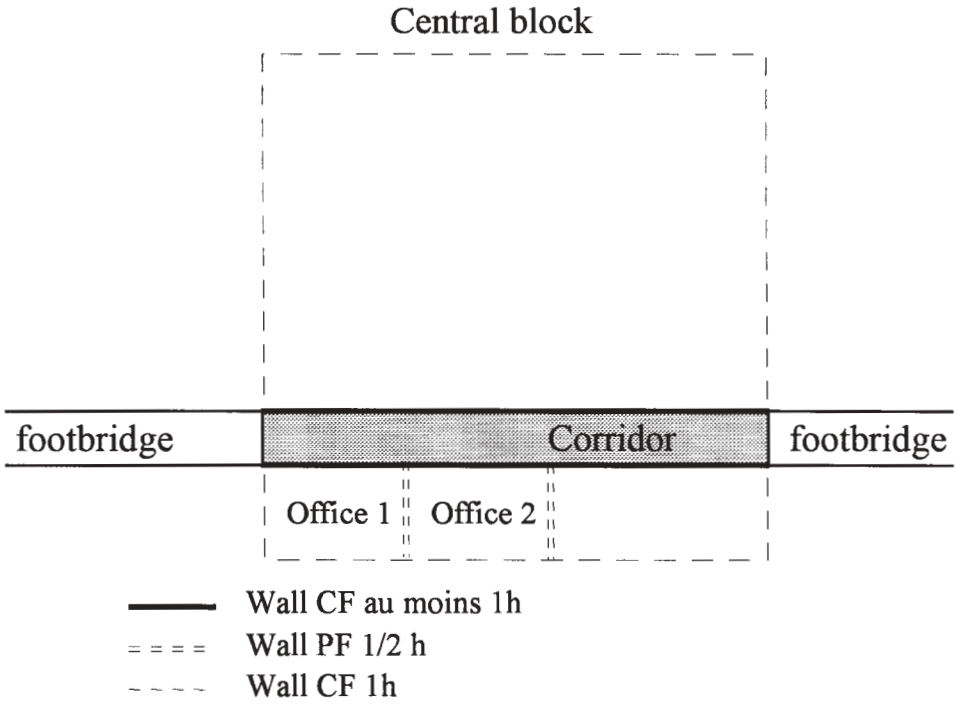


Figure 3.2: Description of the rooms

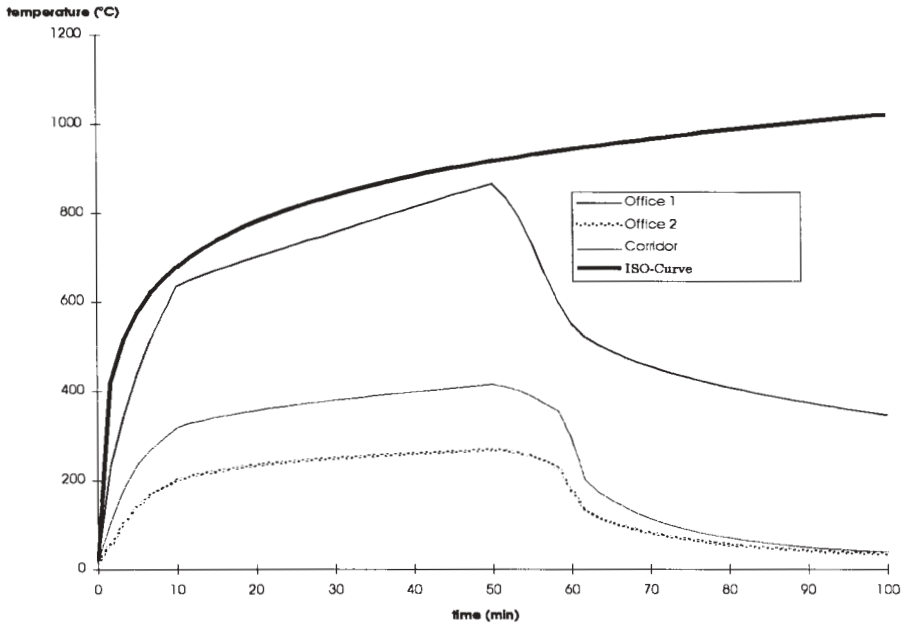


Figure 3.3: Temperatures of the different hot layers

3.2.3.3 Scenario C

In this scenario it was considered a fully developed fire in a large volume. The fire density of such room (considering the blocks covering) is about 5 kg/m2. Assuming some opening dimensions, the temperature of the hot layer in the 'salle des pas perdus' is shown in Figure 3.4.

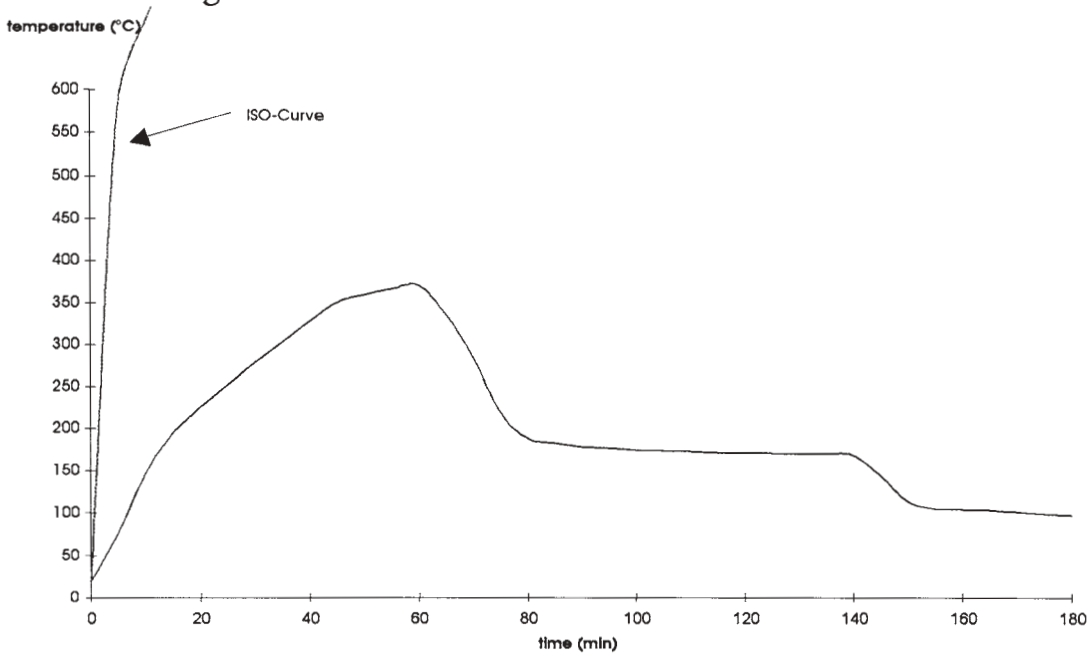


Figure 3.4: Temperature of the hot layer for the scenario C

3.2.3.4 Scenario D

Two localised fire are studied:

- 1500 kg of wood on 15 m^2 (reception)
- 300 kg of wood on 5 m^2 (waiting place)

The empirical equation of Heskestadt is used:

$$T(z) = 25\frac{Q_c^{2/3}}{(z-z_0)^{5/3}} + 20 \qquad (1)$$

Where
z_0 is the virtual origin given by:

$$z_0 = -1{,}02D + 0{,}083Q^{2/5}$$

D diameter (m)
z height (m)
Q heat release (kW)
Q_c convective heat release (kW) (equal to 0,8Q)

The Figure 3.5 gives the evolution of the temperature with the height for both scenarios, assuming to be applied during 30 minutes.

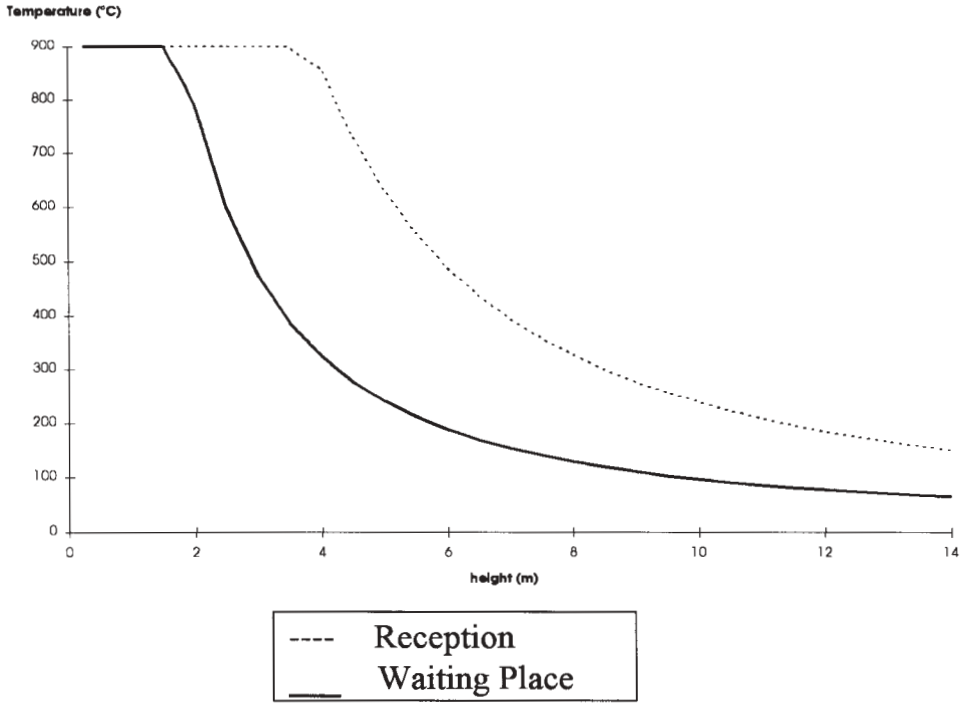


Figure 3.5: temperature versus height for both scenarios

3.2.3.5 Scenario E

For the scenario describing a fire around a column, the assumptions of the scenarios D are used considering that the temperature is applied for structure temperature calculations during 30 minutes giving a temperature of the structure as a function of the height.

3.2.3.6 Scenario F

In this scenario the Annexe C of the Eurocode 1 part 2.2 'actions in case of fire' is used, considering the hypothesis of the scenario B: fire load 5 kg/m2. About openings, it is considered that a glass breaks out leading to the maximum heating of the structure. The structure is a column at about 8m from the facade. The table 1 gives the different results of the method.

	temperature (°C)
compartment	566
window	730
flame	646
structure	225

Table 1: temperature resulting from the external structure method

3.2.3.7 scenario G

This scenario comes from the scenario A. The scenario A assumes that the horizontal window having an ISO-fire rating of 30 minutes keeps its stability during the fire. Nevertheless, the calculated temperature is relatively high and the duration of the fire is more than one hour. According to these results, a simulation considering the break out of the window at the beginning of the fire is necessary.

So it has been assumed the fire in the 'salle d'audience' has a similar development than the scenario A, but the smoke exhausting the room by the horizontal window fills the large volume of the 'salle des pas perdus'. The Figure 3.6 shows the configuration of the building for calculations with the multi-compartment zone model CFAST. The calculated temperature of the hot layers in the 'salle d'audience' and in the 'salle des pas perdus' are shown in Figure 3.7.

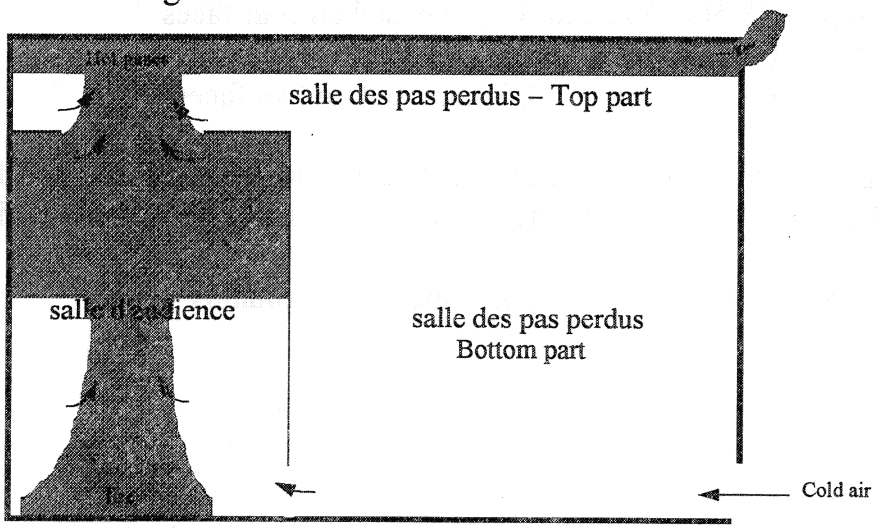


Figure 3.6: Configuration of scenario G

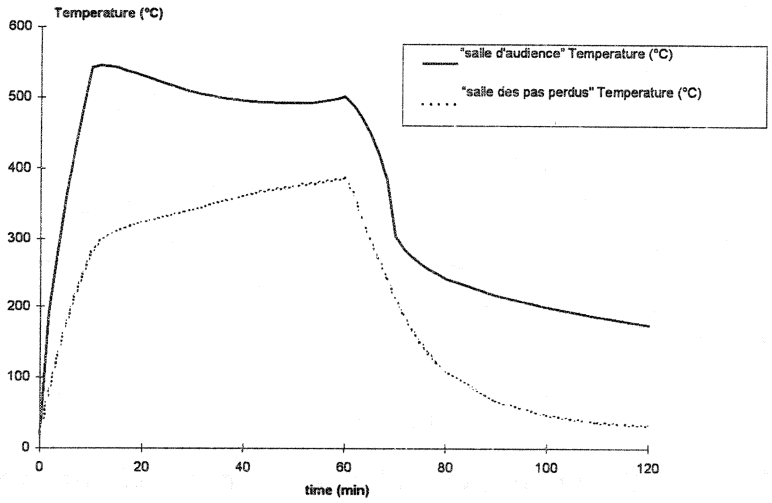


Figure 3.7: Temperature in the case of scenario G

3.2.4 Heat transfer to structure

According to the different results presented here in above, the scenario E is used for internal columns, the scenario F for external columns, and the scenario A and G are used for beams.

A more detailed description of the heat transfer calculations is given in reference [5].

3.2.4.1 internal columns

The Figure 3.5 is used to determine the temperature of the internal columns which are in 3 types:

- Type 1 : tube PRS 500x500X20 (C1) exposed on four faces
- Type 2 : PRS 500x8-500x15 (C4, C5, C6) exposed on one face
- Type 3 : tube PRS 360x360x12 (C7) exposed on two faces

The heat transfer to columns is calculated using the two-dimensional heat transfer model TASEF considering the thermal properties of steel given in Eurocode 3 part 1.2.

The Figures 3.8 to 3.25 show the temperature of the columns

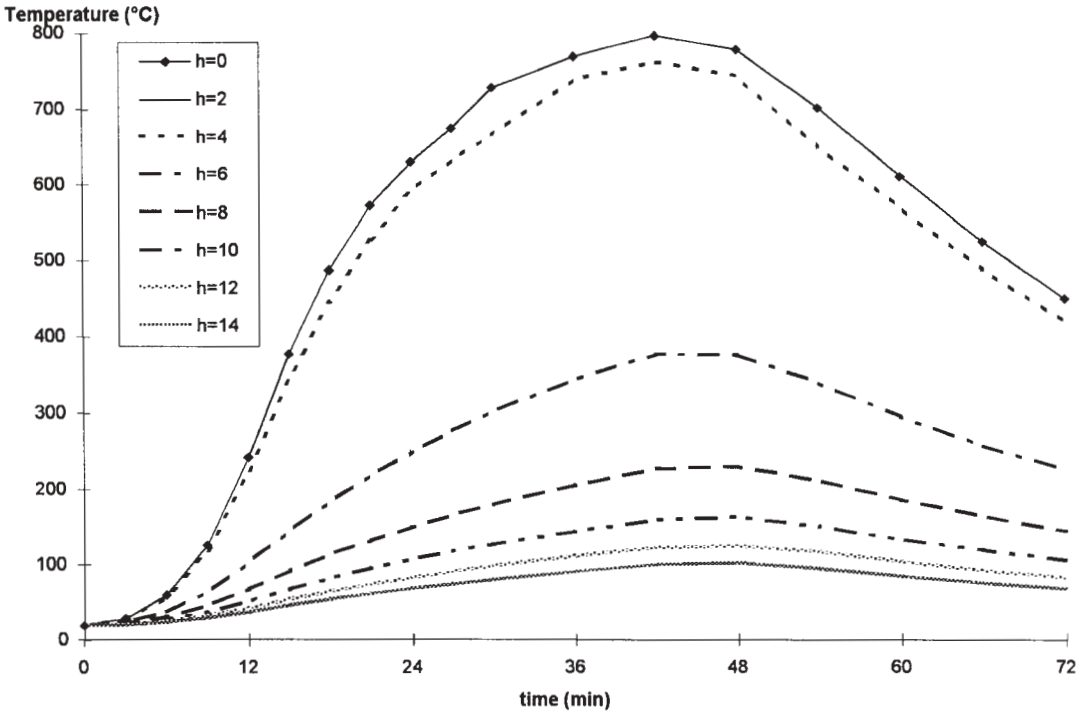


Figure 3.8: Homogeneous temperature of column type 1

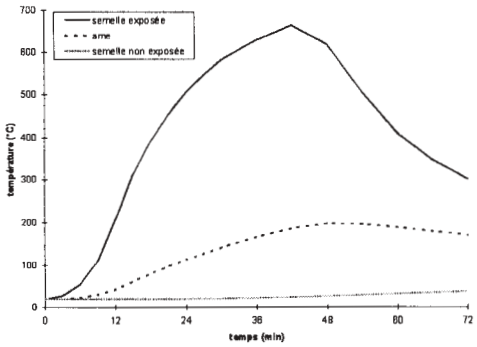


Figure 3.10 : Temperature of the column type 2 at 0 m

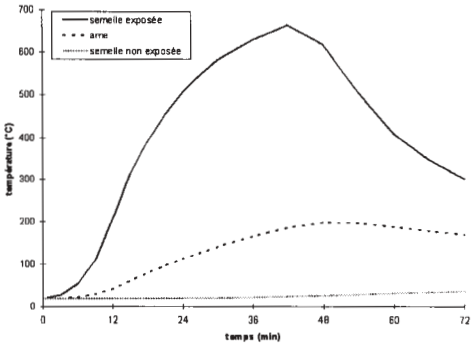


Figure 3.11 : Temperature of the column type 2 at 2 m

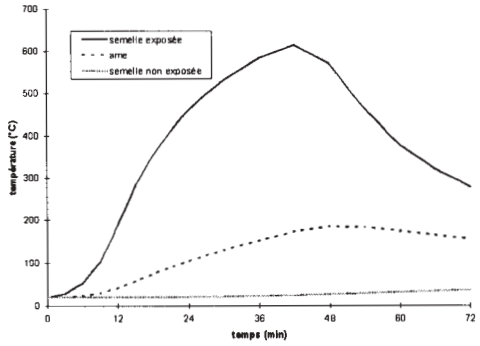


Figure 3.12 : Temperature of the column type 2 at 4 m

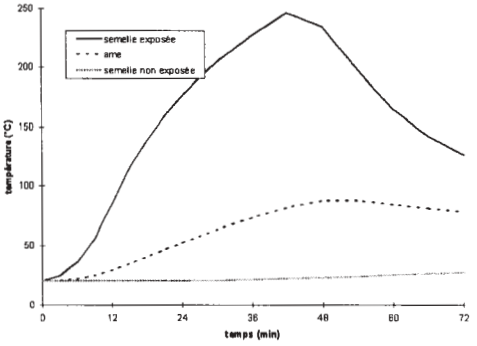


Figure 3.13 : Temperature of the column type 2 at 6 m

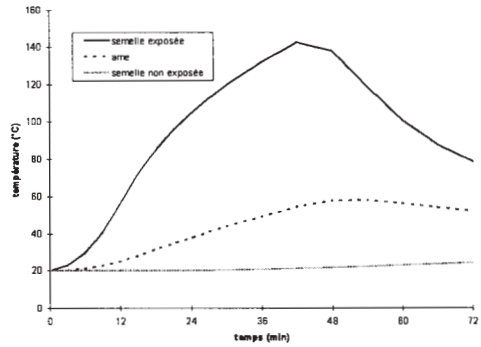


Figure 3.14 : Temperature of the column type 2 at 8 m

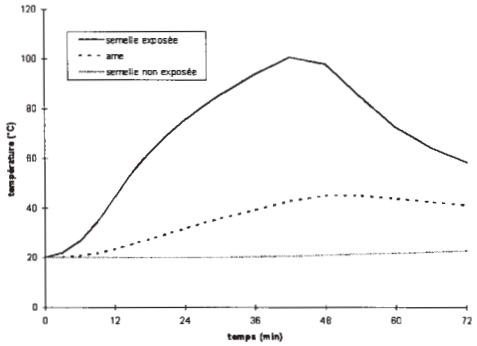


Figure 3.15 : Temperature of the column type 2 at 10 m

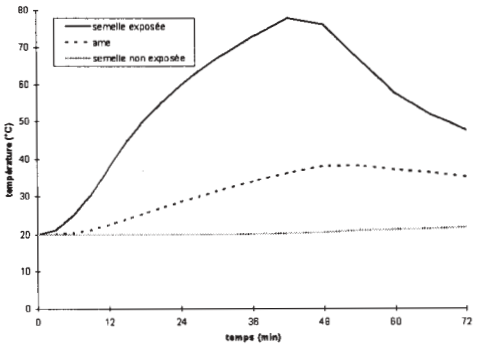


Figure 3.16 : Temperature of the column type 2 at 12 m

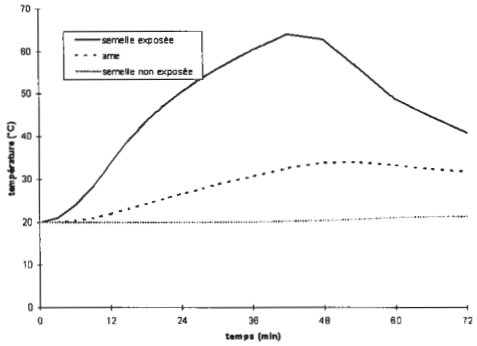


Figure 3.17 : Temperature of the column type 2 at 14 m

Note: Translation: semelle exposée = exposed flange; âme = web

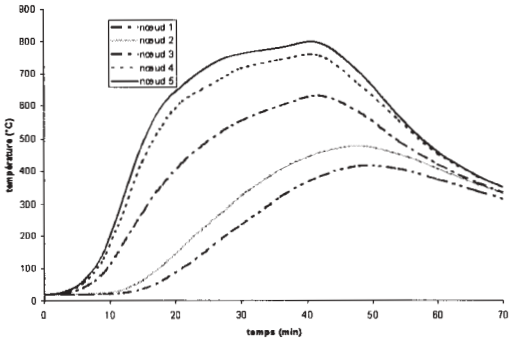


Figure 3.18 : Temperature of the column type 3 at 0 m

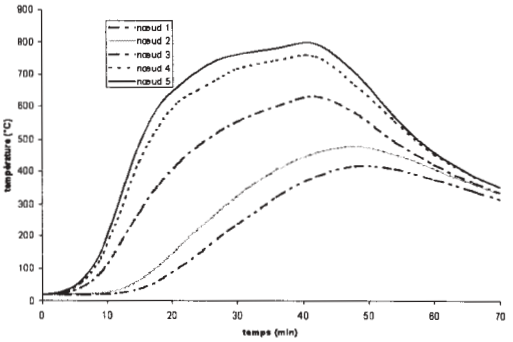


Figure 3.19 : Temperature of the column type 3 at 2 m

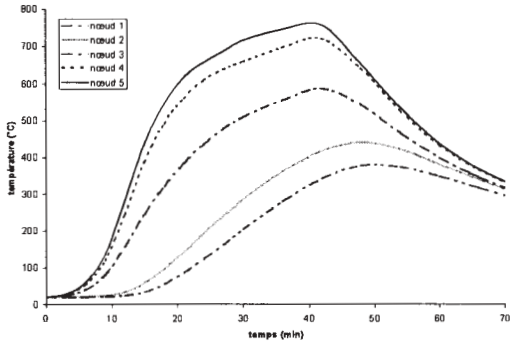


Figure 3.20 : Temperature of the column type 3 at 4 m

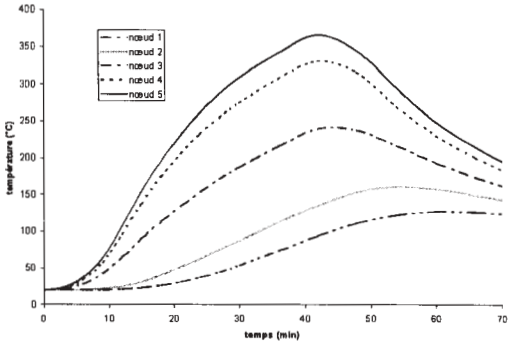


Figure 3.21 : Temperature of the column type 3 at 6 m

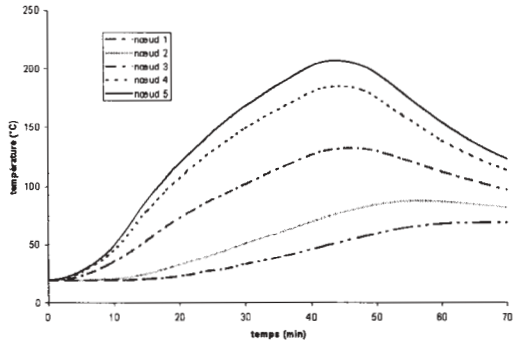


Figure 3.22 : Temperature of the column type 3 at 8 m

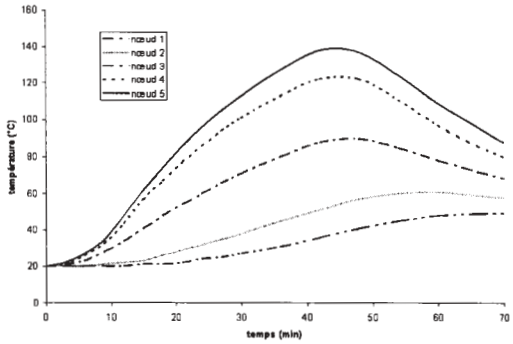


Figure 3.23 : Temperature of the column type 3 at 10 m

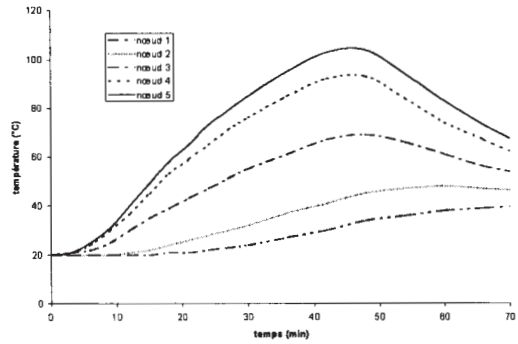


Figure 3.24 : Temperature of the column type 3 at 12 m

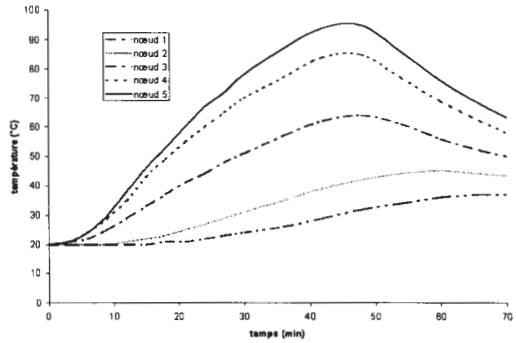


Figure 3.25 : Temperature of the column type 3 at 14 m

Note: Translation: noeud = node

3.2.4.2 external columns

The scenario C is relevant for the external columns at 8m from the façade. It provides a temperature of 225°C

3.2.4.3 Beams

For the beams, the more critical scenarios are the scenarios A and G. For the heat transfer, 4 types of beams are used to assessed the temperature of the beams:

- HEA 550
- IPE 450
- IPE 200
- PRS 1000x10-350x40

3.2.4.3.1 Scenario G

For the scenario G, heat transfer to all the beams localised under the slab of level 4 are heated from the hot layer gases in 'the salle des pas perdus' and a localised heating exists coming from the localised effect above the horizontal window. This localised effect is quantified considering the temperature of the hot layer existing in the 'salle d'audience'.

The Figures 3.26 to 3.29 show the temperature of the upper and lower flanges and of the web of the four types of beam considering the generalised heating.

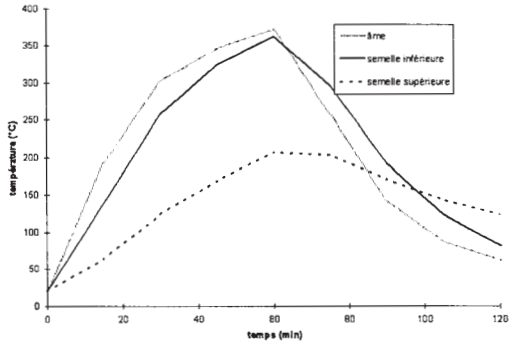


Figure 3.26 : Temperature de section HEA 550

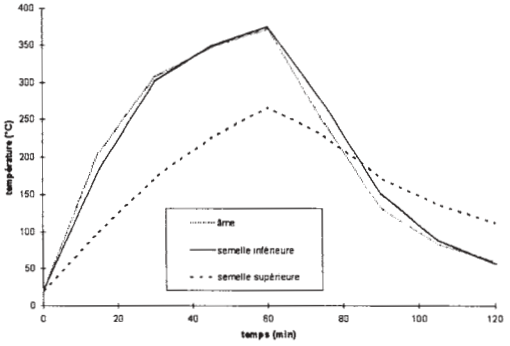


Figure 3.27: Temperature de section IPE 450

Note: Translation: âme =web; semelle inférieure = bottom flange
semelle supérieure = top flange

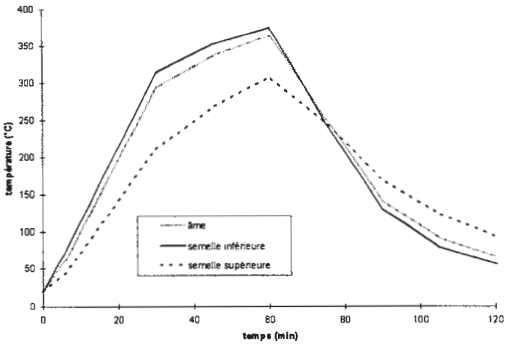


Figure 3.28 : Temperature de section IPE 200

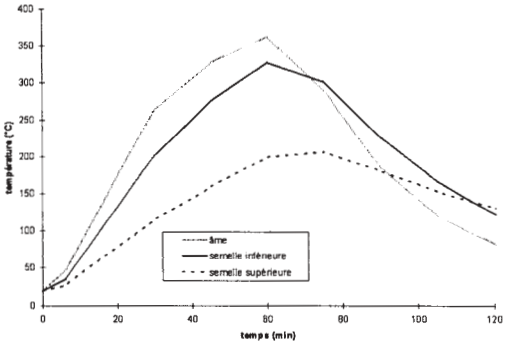


Figure 3.29 : Temperature de section PRS 1000

The Figures 3.30 to 3.33 show the temperature of the upper and lower flanges and of the web of the four types of beam considering the localised heating.

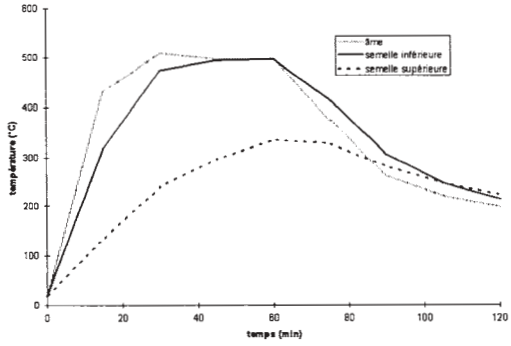


Figure 3.30 : Temperature de section HEA 550

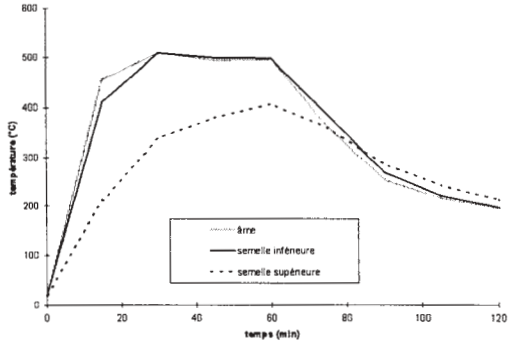


Figure 3.31 : Temperature de section IPE 450

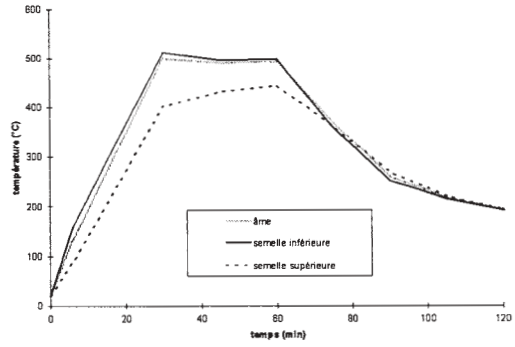


Figure 3.32 : Temperature de section IPE 200

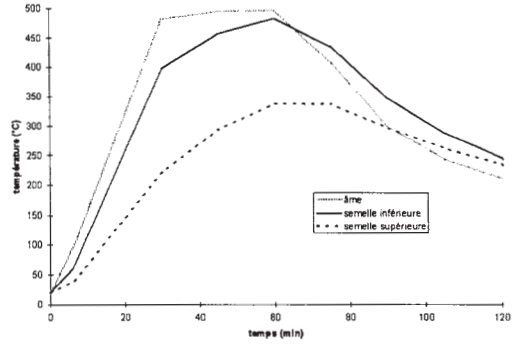


Figure 3.33: Temperature de section PRS 1000

Note: Translation: âme =web; semelle inférieure = bottom flange
semelle supérieure = top flange

3.2.4.3.2 Scenario A

The scenario A is relative to a fire development in the 'salle d'audience'. So the heating of the structure is only made by radiation from the horizontal window. So the structure localised above this window may be heated.

So the radiative flux from the window (considered at the temperature given by Figure 3.1) is determined. The view factor from the beam to the window is also determined in order to calculate the steel temperature. Different points are taken in order to calculate a spatial repartition of temperature. These points are shown in Figure 3.34.

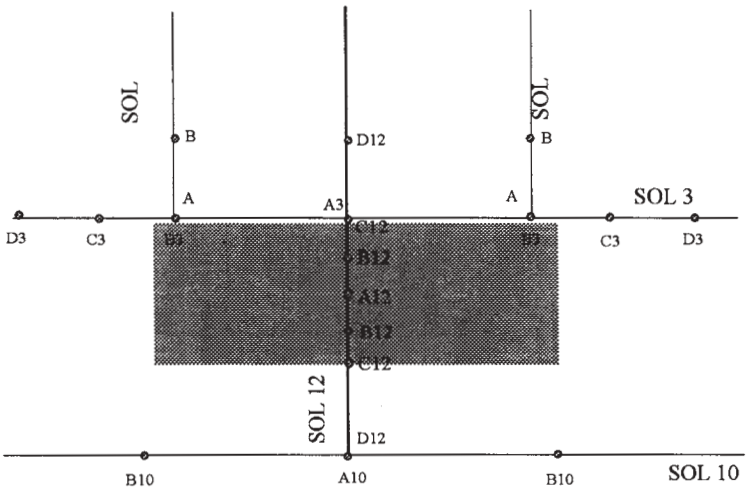


Figure 3.34: repartition of points for temperature calculations

The Figures 3.35 to 3.38 give the temperature of the beams localised above the window.

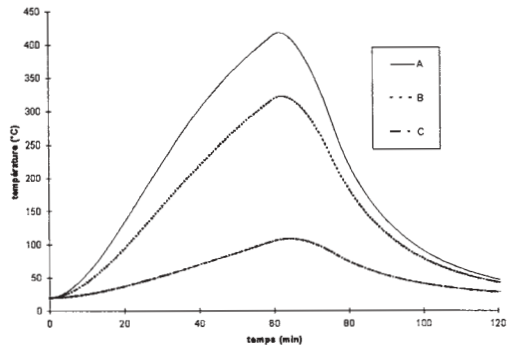


Figure 3.35 : Temperature of the profile SOL

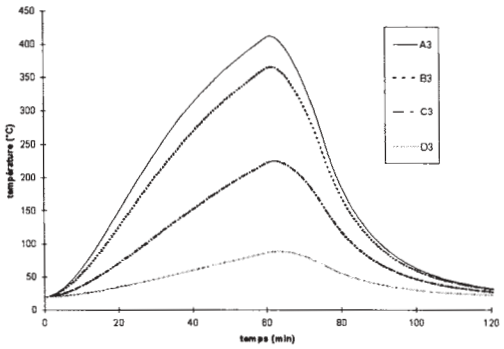


Figure 3.36 : Temperature of the profile SOL 3

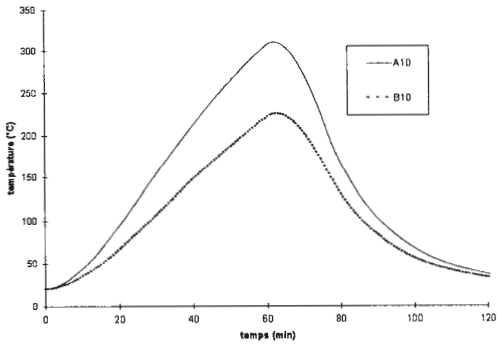


Figure 3.37 : Temperature of the profile SOL 10

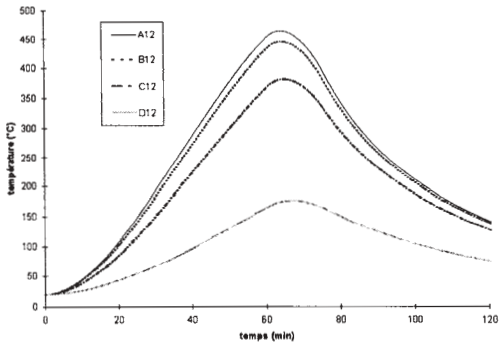
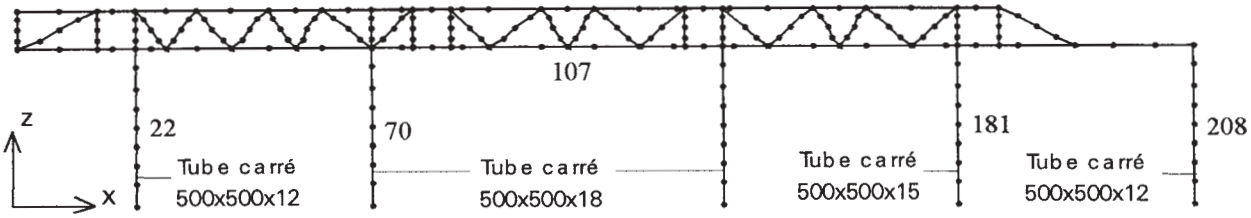


Figure 3.38 : Temperature of the profile SOL 12

3.2.5 Mechanical behaviour

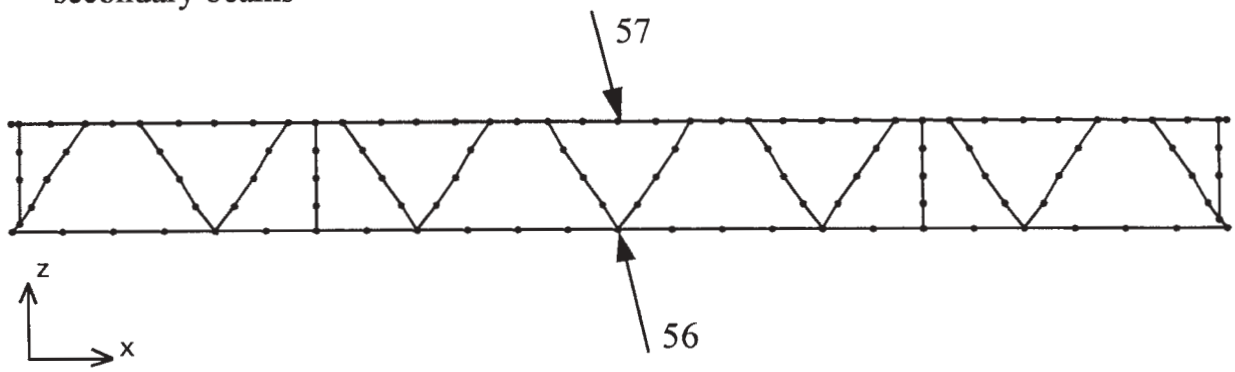
Three different structure are modelling:

- primary beams with columns

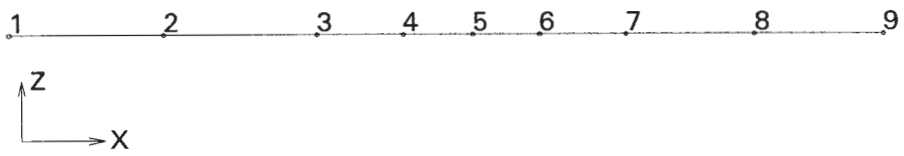


Note: translation : Tube carré = square tube

- secondary beams



- tertiary beams



More details about this fire behaviour of the structure are given in reference [1].

The action combinations are given by the Eurocode part 2.2 + French DAN [6]. The two combinations taken into account for the present calculations are the following:

Imposed load: $\sum_{j\geq 1} G_{kj} + 0{,}7 \cdot Q_k$

Snow load: $\sum_{j\geq 1} G_{kj} + 0{,}6 \cdot Q_k + \sum_{i\geq 1} 0{,}2 \cdot Q_{ki}$

The mechanical behaviour of the structures is determined by the code LENAS [4] of CTICM considering the steel mechanical law of the Eurocode 3 part 1.2 [3].

3.2.5.1 primary beams

The most critical case for the primary beam is the scenario G. For the primary truss beam, only the lower beam localised in the 'salle des pas perdus' is heated. The other part of the truss is situated in the level 4 separated by a 90 minutes ISO-fire rating from the level 1.

The Figure 3.39 shows the deformation of the primary beam at 60 minutes.
The Figure 3.40 gives the vertical displacement of the node 107 as a function of time.

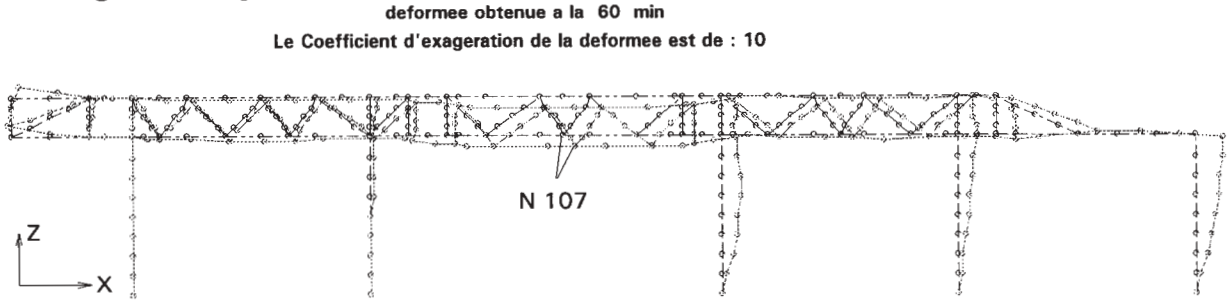


Figure 3.39: Deformation of the structure at 60 minutes (the displacements have been multiplied by 10)

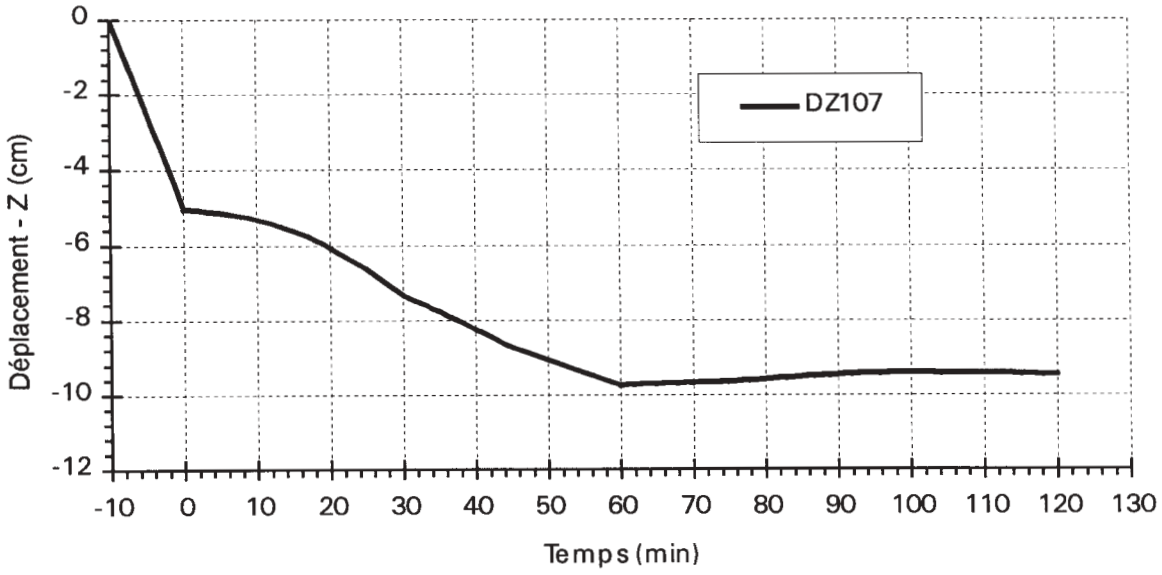


Figure 3.40: vertical displacement of node 107

3.2.5.2 secondary beam

The scenario G is the most critical scenario for the secondary beam. For the secondary truss beam, only the lower chord localised in the 'salle des pas perdus' is heated. The other part of the truss is situated in the level 4 separated by a 90 minutes ISO-fire rating from the level 1.

The Figure 3.41 shows the deformation of the primary beam at 60 minutes.
The Figure 3.42 gives the vertical displacement of nodes 56 & 57 as a function of time.

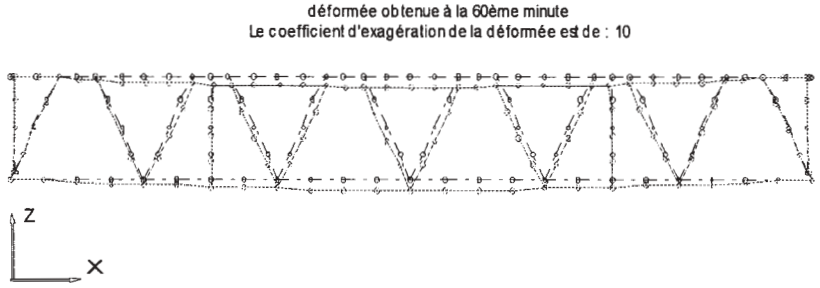


Figure 3.41: deformation of the structure at 60 minutes (the displacements have been multiplied by 10)

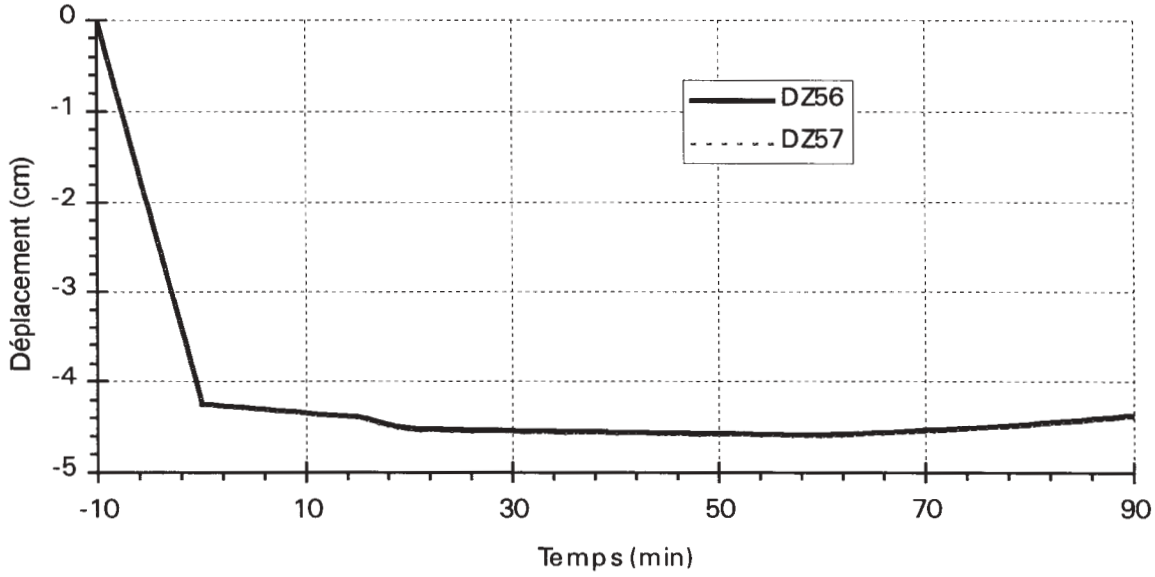


Figure 3.42: vertical displacement of nodes 56 and 57

3.2.5.3 internal columns

3.2.5.3.1 columns type 1

The fire behaviour of the column type 1 is studied by the structural modelling of primary beam.

The Figure 3.43 gives the horizontal displacement of the node 181 showing a failure at 20 minutes.

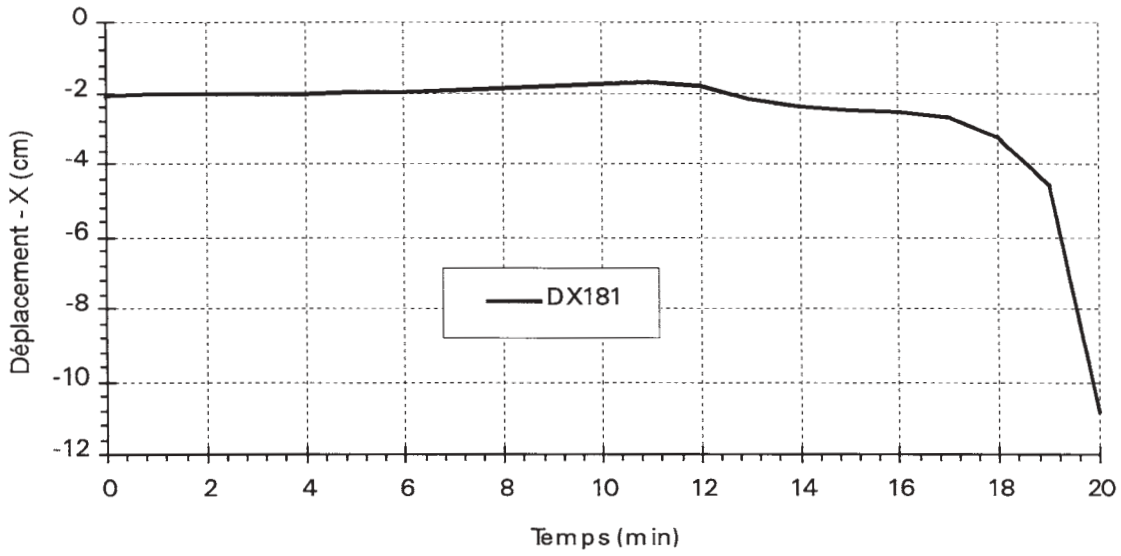


Figure 3.43: horizontal displacement of the node 181 (column)

3.2.5.3.2 columns of type 2

These columns are heated only by one side. The column is modelled alone. The Figure 3.44 gives the horizontal displacement of the node corresponding at the half of the column height.

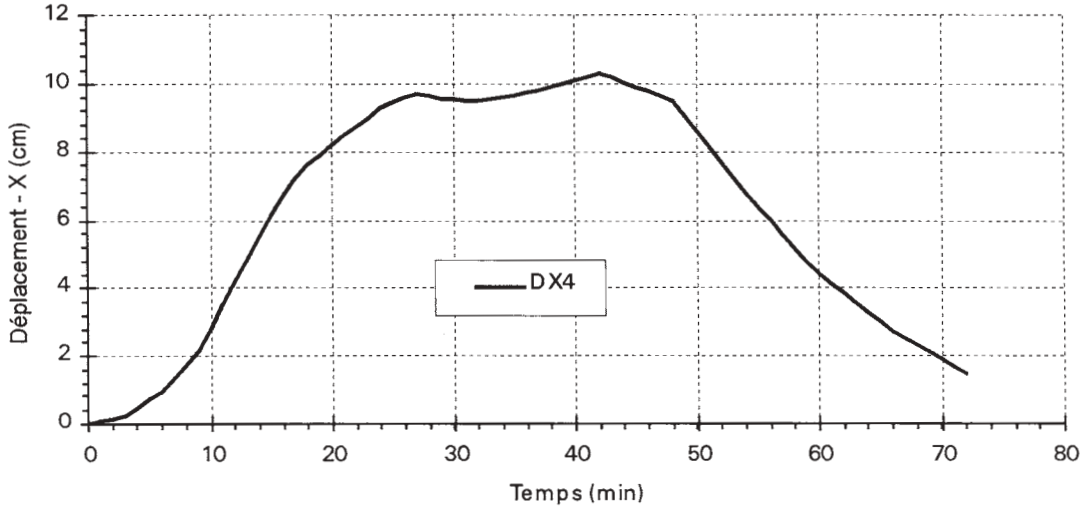


Figure 3.44: horizontal displacement of node at the half of the column height

3.2.5.3.3 columns of type 3

These columns with a square section are heated only by two sides. The column is modelled alone. The Figure 3.45 gives the horizontal displacement of the node corresponding at the half of the column height. This figure indicates a failure of the column at 38 minutes during the decreasing phase of the fire.

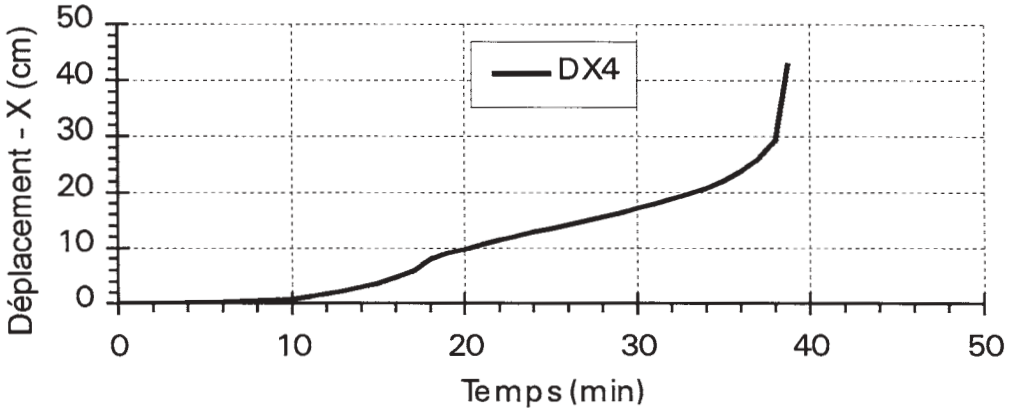


Figure 3.45: horizontal displacement of node at the half of the column height

3.3 CONCLUSION

A natural fire safety concept has been applied to justify the steel structure inside the level 1 of the new building: palais de justice de Nantes. The natural heating curves have been deduced by using Two Zone Models, Annex C of ENV 1991-2-2 for external columns and Heskestadt Formula for internal columns (see WG1 report).

Due to the size of the compartment which implies a stratification into two zones (Hot zone at the top and Cold zone at the bottom), the program OZONE and the design fire load included the effect of the active measures has not been used. Moreover there is here no sprinkler and no automatic connection to the fire brigade.

Three phases has been defined:

- fire scenarios definition
- fire development assessment
- calculations of heat transfer to structural elements
- determination of the structural behaviour

The scenario definition phase has constituted 8 scenarios that have generated 8 calculations of fire development.

After these calculations, 4 scenarios have been defined as the most critical for beams and columns.

From these 4 scenarios, more than 50 heat transfer calculations to structural elements have been done.

From these heat transfers, the mechanical behaviour of the structure has been determined.

From these fire-engineering calculations and from the assumptions used in the study, it can be concluded:

- the stability of the beams under the slab of the level 4 is verified in case of fire development in the level 1, 2 and 3
- the stability of the columns type 2 and external columns is also verified
- the internal columns type 1 and type 3 need a fire protection.

3.4 REFERENCES

[1] D. DHIMA " Vérification du comportement au feu de la structure métallique du plate-forme du niveau 4 dans l'hypothèse d'un incendie dans la salle des pas perdus – phase 3 : comportement mécanique ", INC - 98/236 - DD/NB

[2] D. JOYEUX " Vérification du comportement au feu de la structure métallique du plate-forme du niveau 4 dans l'hypothèse d'un incendie dans la salle des pas perdus – phase 1 : Proposition des Scénarios d'incendie ", INC - 98/50b - DJ/IM

[3] Norme XP ENV 1993-1-2 (Eurocode 3 - D.A.N., partie 1-2 : Calcul du comportement au feu des structures en acier), mai 1997

[4] H. KANEKO
Etude par la méthode des éléments finis en comportement mécanique d'éléments plaques en acier soumis à l'incendie
Revue CM, n° 1 (1990)

[5] D. JOYEUX " Vérification du comportement au feu de la structure métallique de la plate-forme du niveau 4 dans l'hypothèse d'un incendie dans la salle des pas perdus – phase 2 : Température des éléments de structure ", INC - 98/191 - DJ/NB

[6] Norme XP ENV 1991-2-2 (Eurocode 1 - D.A.N. part 2.2 : Actions en cas d'incendie) février 1995

[7] " règlement de sécurité incendie dans les Etablissements Recevant du Public ",

ANNEX 4

4. THE OBSERVATORY OF THE CITY IN THE ANCIENT DUCAL STABLE IN URBINO, ITALY

4.1 THE BUILDING

In the Data of Urbino were the ancient Ducal Stable. Moreover this building with its particular dimensions, internal length 127,08 m, internal width 9,88 m, were an element of connection, also perspective, between the southern front of the Ducal Building and the wide surface of the Mercatale (see Figures 4.2 to 4.4).

The building which we find today is a long facade having the same elegance of the Ducal Building. Moreover a beautiful garden lies at the ground floor of the building. Task of the project is to preserve these images retaining the remains of the ancient building, keeping its continuity function and providing the new building of a series of tree-lined areas.

The new building will be destined at Observatory of the City and it will appear as a long space where are various smaller areas having different functions: picture gallery, cartography exhibition, archaeological exhibition, craftsmanship and an area for library and archives.

To the various internal spaces there are three accesses: the first is through the central staircase from the downstairs entrance, the others from the extreme parts of the building.

4.2 THE STRUCTURE

The new building frame is independent on the existing walls where it is contained. Roofing are realised by galvanised corrugated sheet, floors by corrugated sheet with concrete, beams and columns by H shaped steel profiles.

4.3 NATIONAL FIRE SAFETY REQUIREMENTS

At this state of the design an area of about 350 m^2 is destined at the function of library and archives. Together with the national authorities it has been decided to consider a medium fire load of 700 MJ/m^2 for all the areas of the building.

According to the Italian regulation, 90 minutes ISO fire resistance is required for the steel structures of the building.

4.4 NATURAL FIRE SAFETY CONCEPT APPLICATION

4.4.1 Introduction

It is our aim to evaluate the characteristic of a real fire in the building.
For the whole volume of the building, except the three main staircases, no one compartimentation is present, neither vertical nor horizontal. For this, only one fire scenario has been considered for the total building volume.

4.4.2 Fire scenario

It corresponds to a fully engulfed fire compartment with these characteristics:

Fire area
$A_f = 1.795\ m^2$

Openings
Eleven openings are present:

$A_{1w} = 3{,}00 \cdot 10{,}80 = 32{,}40\ m^2$	in the first garden area
$A_{2w} = 3{,}00 \cdot 6{,}40 = 19{,}20\ m^2$	in the second garden area
$A_{3w} = 3{,}00 \cdot 6{,}40 = 19{,}20\ m^2$	in the third garden area
$A_{4w} = 8 \cdot 1{,}60 \cdot 4{,}20 = 53{,}76\ m^2$	8 windows in the longitudinal wall
$A_{5w} = 4 \cdot 1{,}50 \cdot 10 = 60\ m^2$	4 transversal opening in the roofing

Thermal properties of boundaries
For the boundaries of the compartment the following materials are assumed:

roofing:	steel corrugated sheet
walls:	brick
pavement:	concrete

Rate of Heat Release curve

characteristic fire load:	$q_{k,f} = 700\ MJ/m^2$	
combustion factor:	$m = 1$	
fire activation danger:	$\gamma_{q1} = 1{,}46$	
	$\gamma_{q2} = 0{,}85$	area for museum and exhibition
active fire fighting measures:	automatic fire detection	0,8
	alarm transmission to Fire Brigade	0,9
	Standard Fire Brigade	0,73
	$\gamma_n = 0{,}53$	
design fire load:	$q_{d,f} = q_{k,f}\ \gamma_q\ \gamma_n = 460\ MJ/m^2$	
propagation factor:	$t_\alpha = 300$ sec	
flashover temperature:	500°C	

4.4.3 Results

OZONE model has been used for the fire modelling of the compartment. In the following figure are reported the ISO gas temperature for the first 90 minutes, the OZONE gas temperature and the respective steel temperature in the steel protected profile of roofing during the natural fire.

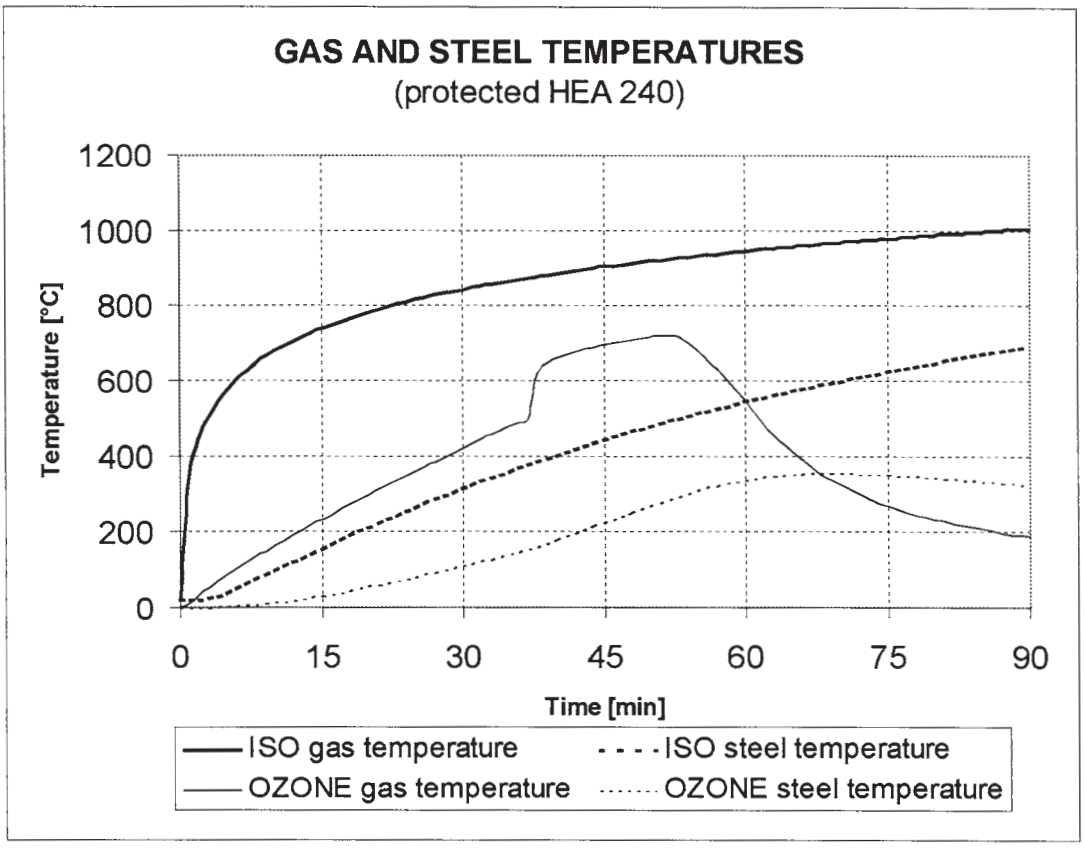


Figure 4.1 : Gas and steel temperatures

4.5 CONCLUSION

One scenario has been defined and a natural fire safety concept has been applied.

Excluding the case of localized heating of the beams depending from the fire load arrangement, not defined at this state of the project, 90 minutes ISO fire protection are resulting too severe for the beam of roofing.

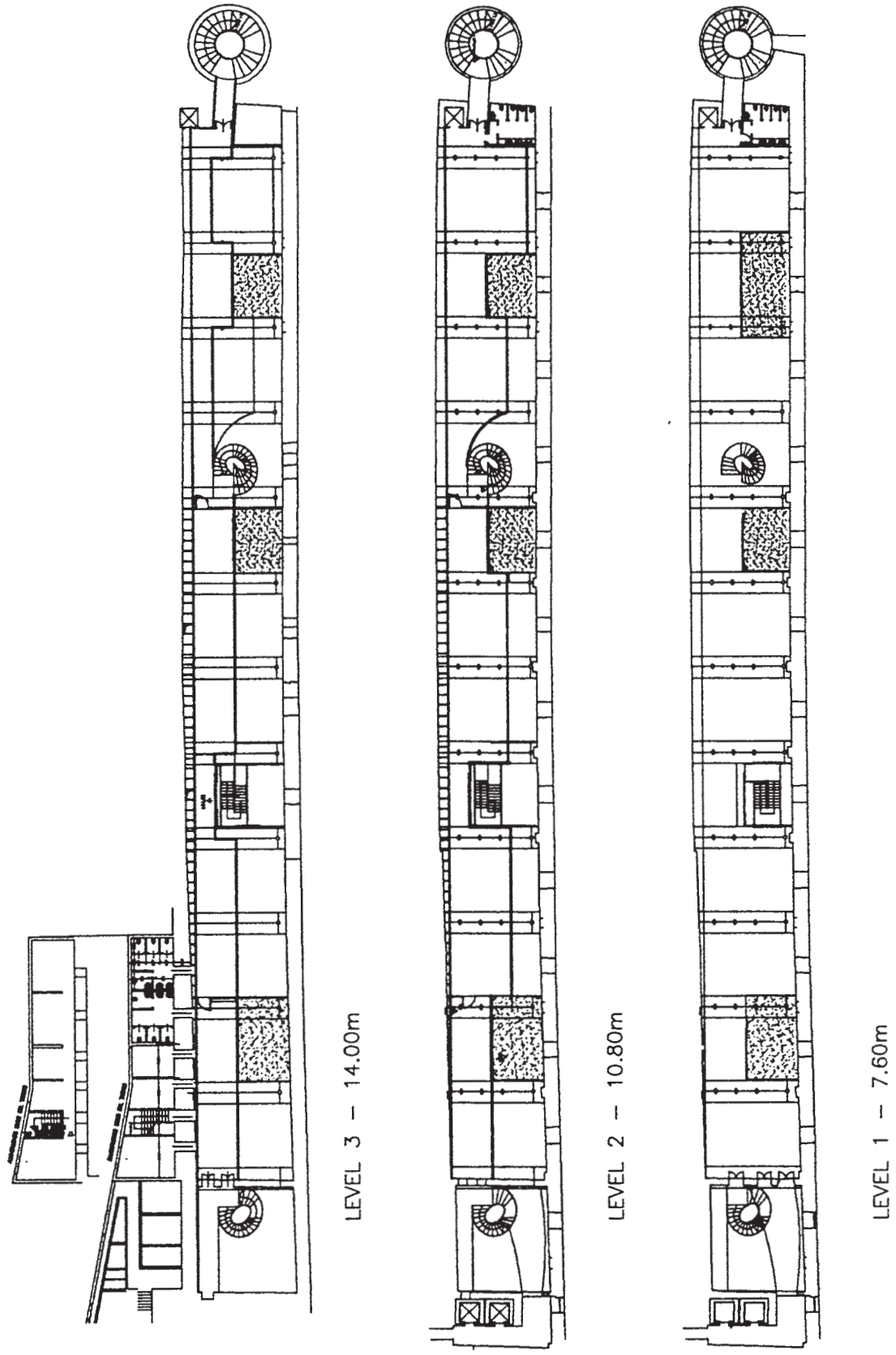


Figure 4.2

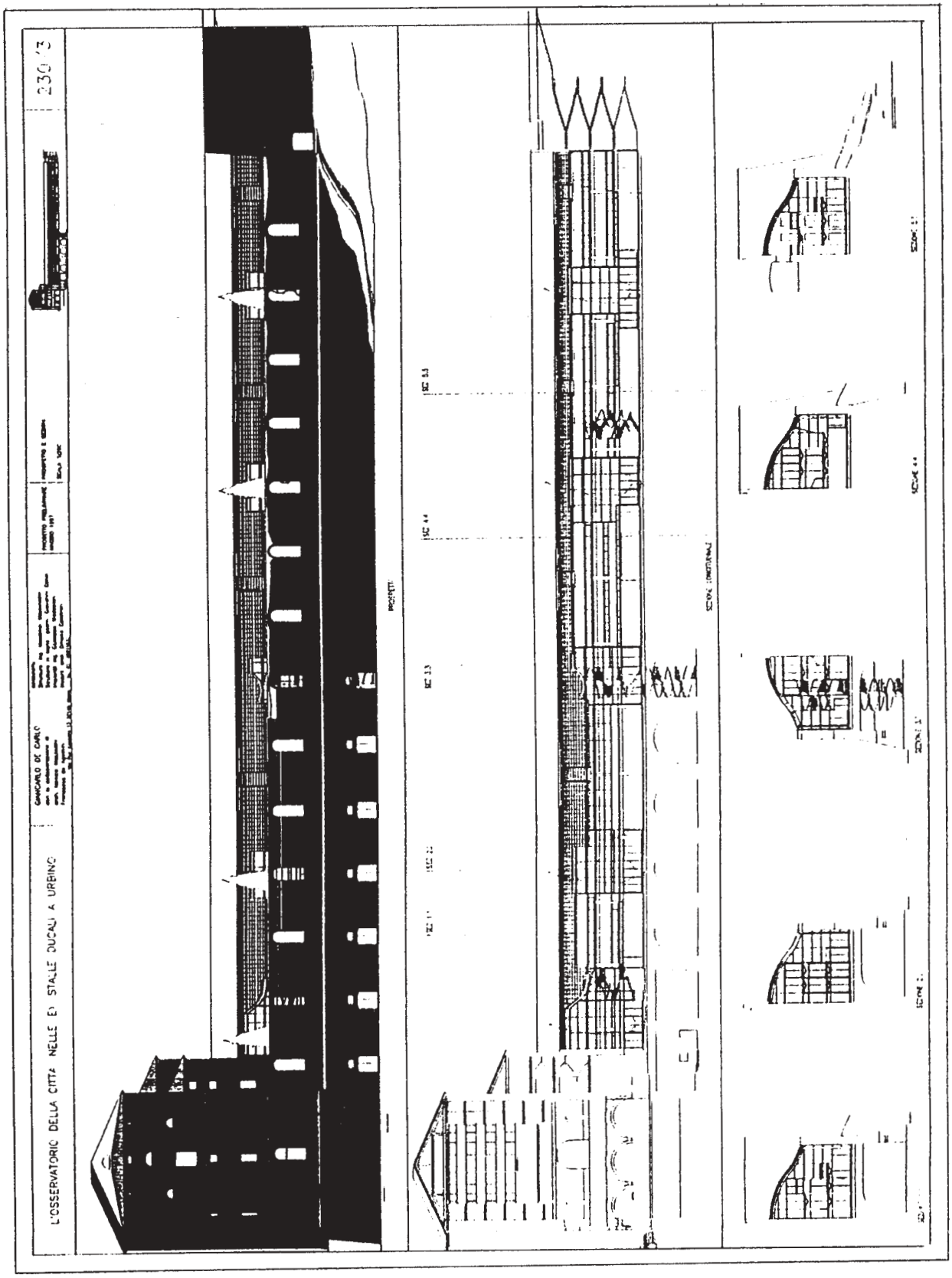
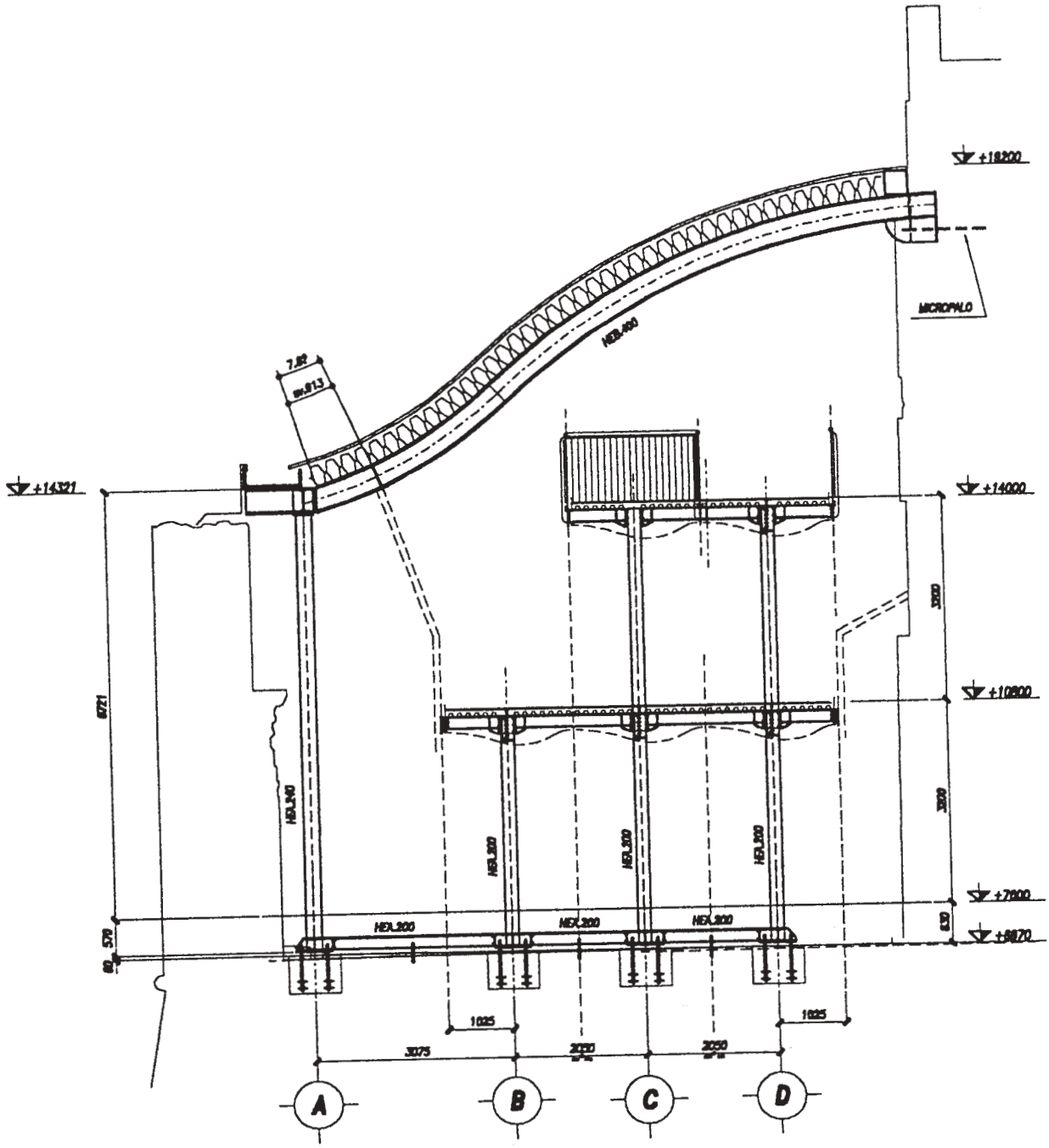

L'OSSERVATORIO DELLA CITTÀ NELLE EX STALLE DUCALI A URBINO
GIANCARLO DE CARLO
PROGETTO PRELIMINARE
PROGETTO E DIREZIONE
PROSPETTI
SEZIONI LONGITUDINALI

Figure 4.3



SEZIONE SUL PICCH.6

Figure 4.4

ANNEX 5

5 OFFICE BUILDING IN MADRID, SPAIN

5.1 GENERAL DESCRIPTION

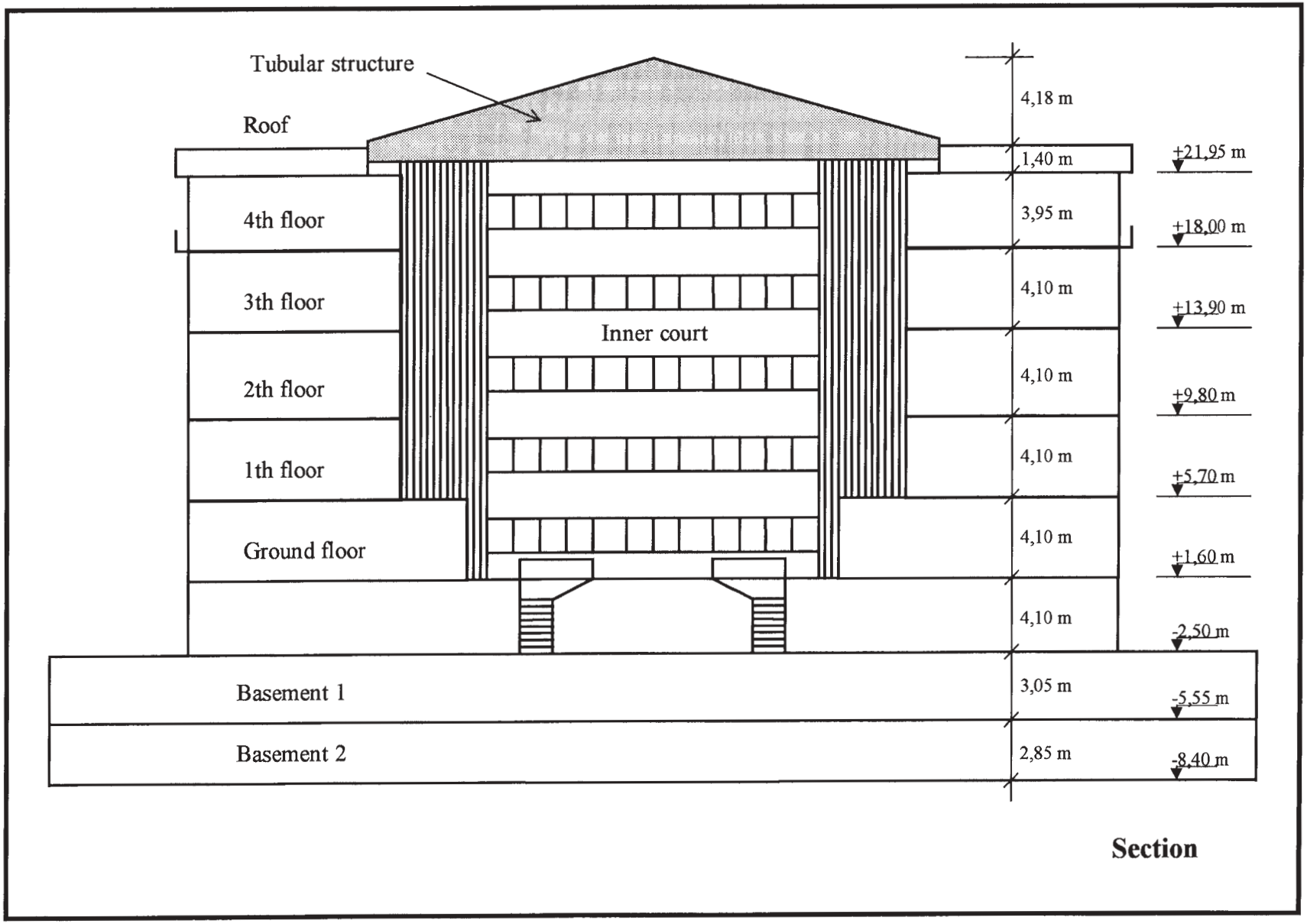
Present study shows the results and the advantages of applying the Natural Fire Safety Concept method developed for large compartments based on the expected fire in a building. This method represents a useful alternative to the actual prescriptive codes and take opportunity from the door opened by local regulations to use these kind of methods.

The analyzed case is that of an existing building in "Parque de las Naciones" in Madrid, Spain. This building is an office building with four floors, an intermediate storey and two basements. The surface area and the volume of each floor are in the following table :

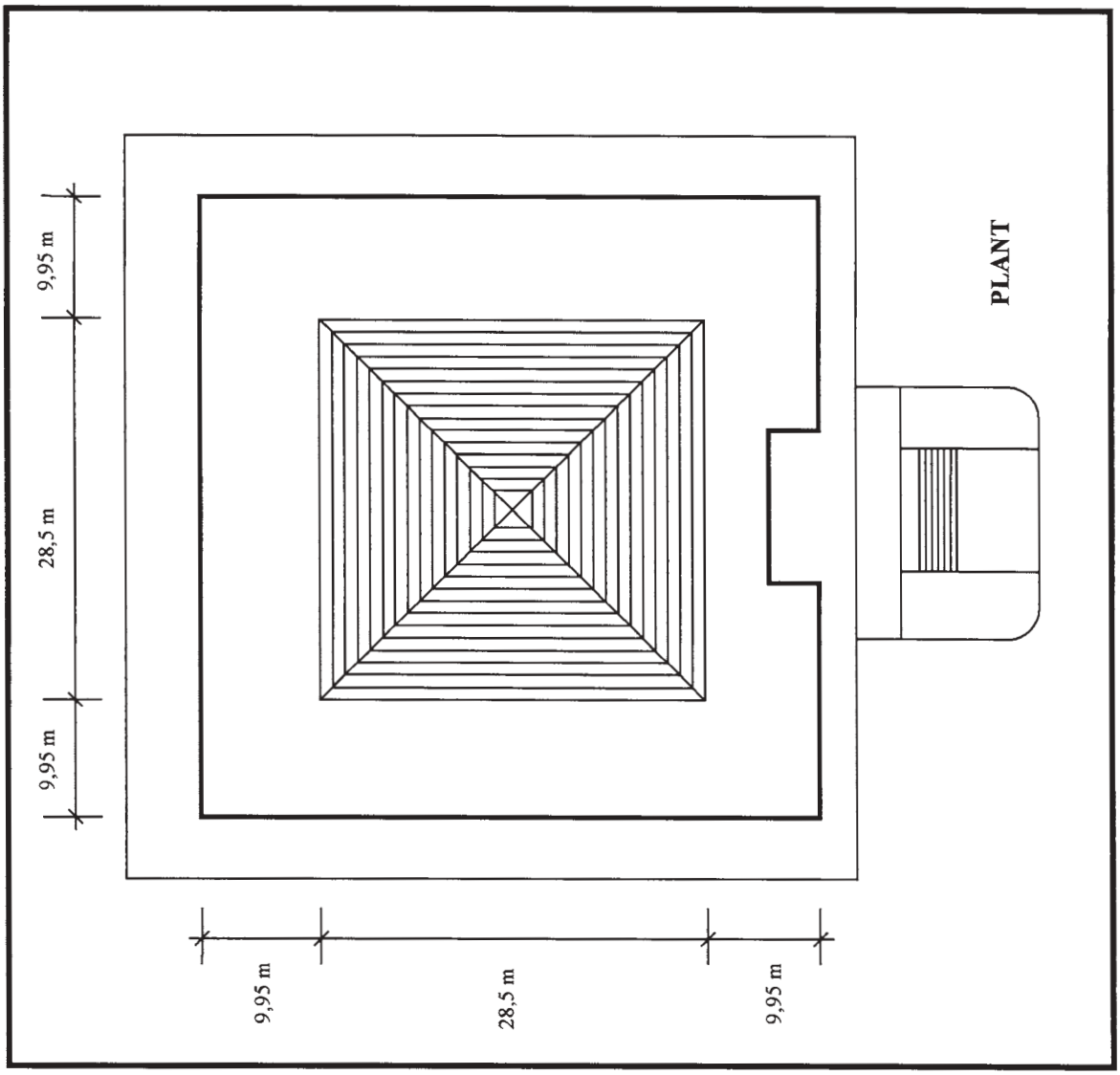
	Area (m^2)	Volume (m^3)
Fourth Floor	1.214	4.306
Third Floor	1.254	4.453
Second Floor	1.254	4.453
First Floor	1.254	4.453
Ground Floor	1.619	5.748
Int. Storey	2.408	8.550

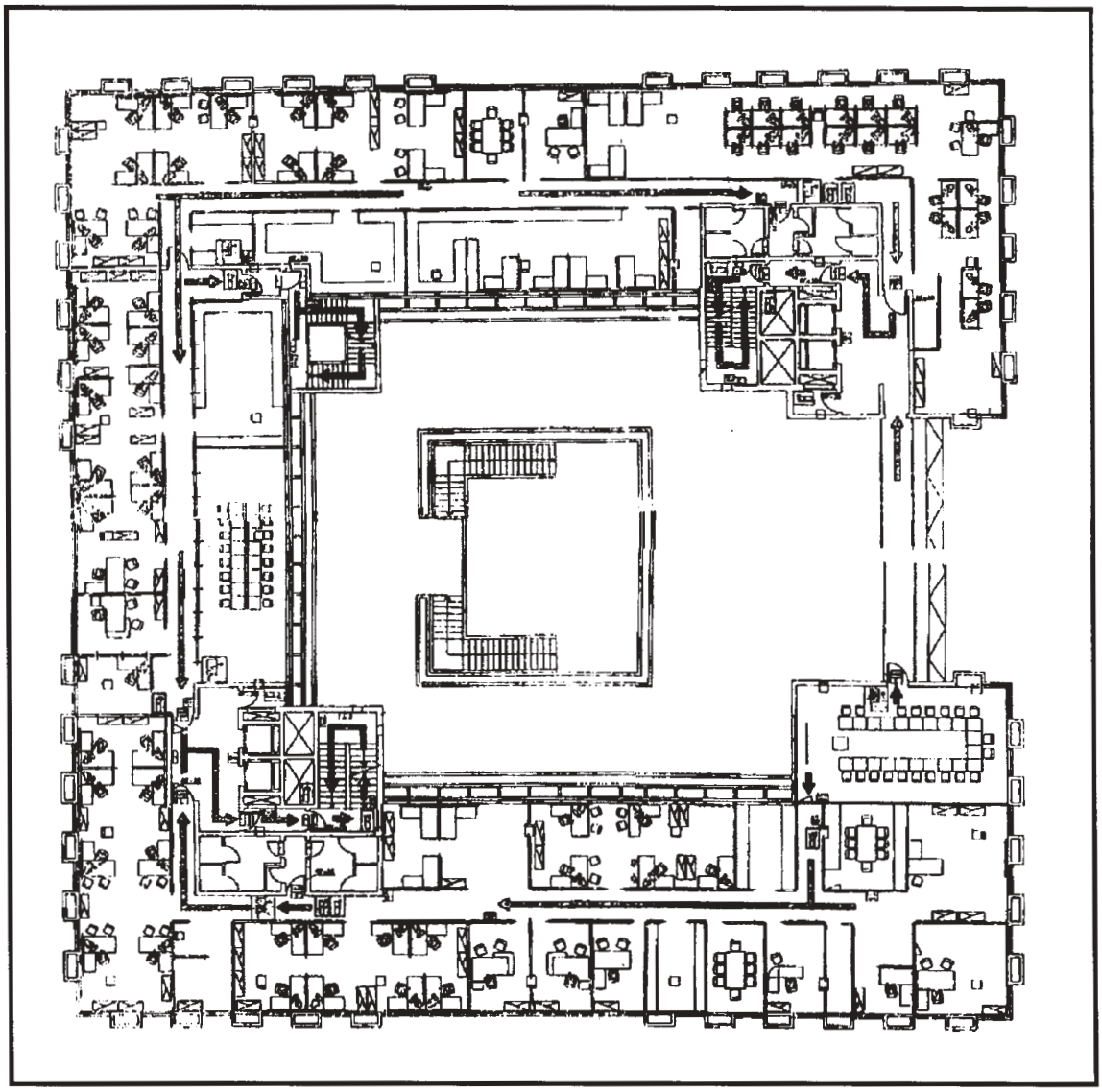
The building has an interior court covered by a translucent roof lying on a spatial steel structure. This structure represents the object of the study. It is a pyramidal steel structure composed by 4.795 tubular profiles, with diameter ranging from 40 to 75 mm and thickness varying from 2 to 3 mm. The external perimeter of the steel structure leaves an open ventilation area of 1,40 meters height.

The following pictures describe the building dimensions and the location of its different parts.


Tubular structure
Roof
4th floor
3th floor
Inner court
2th floor
1th floor
Ground floor
Basement 1
Basement 2
4,18 m
1,40 m
3,95 m
4,10 m
4,10 m
4,10 m
4,10 m
3,05 m
2,85 m
+21,95 m
+18,00 m
+13,90 m
+9,80 m
+5,70 m
+1,60 m
-2,50 m
-5,55 m
-8,40 m

Section


PLANT
9,95 m
28,5 m
9,95 m
9,95 m
28,5 m
9,95 m



5.2 METHODOLOGY

It is our aim to show that the spatial structure which is supporting the glass cladding of the atrium of the office building has a fire resistance of 30 minutes before reaching collapse.

Two basic methods have been applied in order to show that the structure is capable of withstand the most serious fire prone to happen.

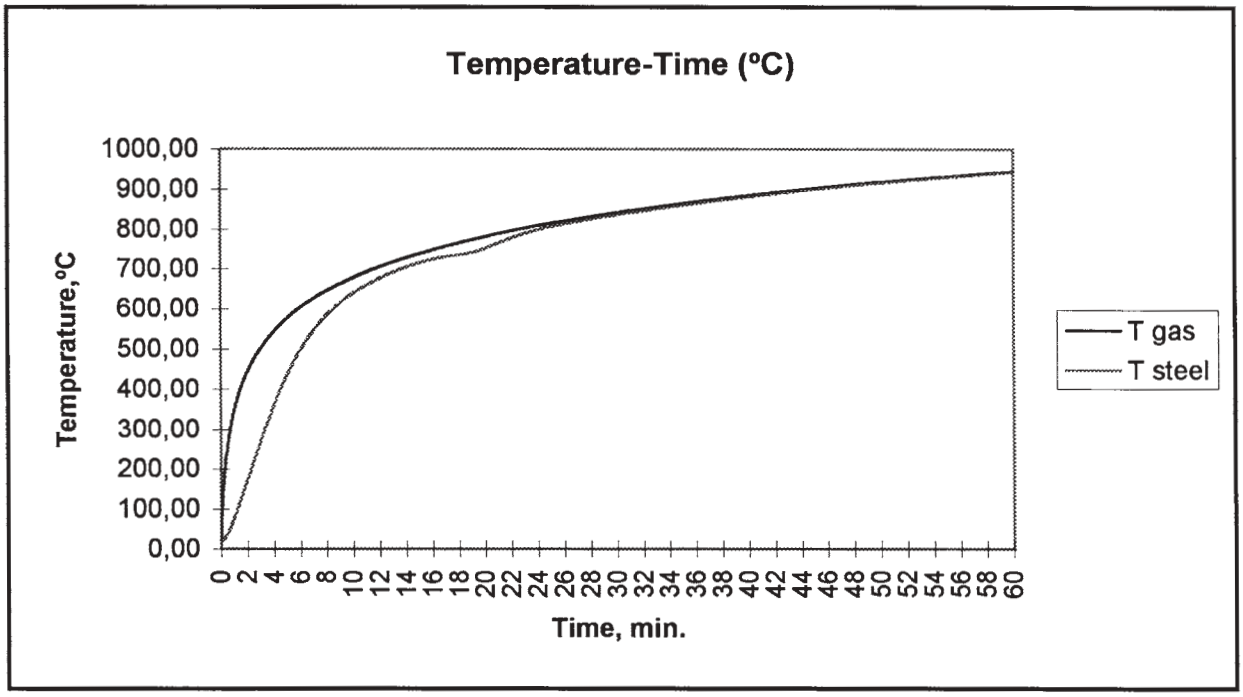
1°- In a first approach, the Standard ISO 834 fire curve is assumed as the design fire in the analyzed enclosure. This curve is used in order to apply the analytical method described in paragraphs 4.2.4 and 4.2.5 of Eurocode 1993-1-2:1995. Assuming a critical temperature of 550°C collapse will happen when any of the structural elements reaches this temperature.

2°- The second approach is mainly different from the first one since the Standard ISO 834 fire is not assumed anymore. Instead, an expected real fire is assumed according to different characteristics of the building. The design tool for steel structures subjected to natural fires in large compartments TEFINAF has been used to assess the temperature of the steel members of the structure (see WG1 report).

5.3 RESULTS

Method 1

As explained before ISO-834 curve is employed as gas temperature and according to ENV1993-1-2:1995 the following temperature-time curve is obtained for a hollow profile of 2 mm thickness (500 m^{-1} section factor):



Obtained results show that if a critical temperature of 550°C is accepted the structure would collapse after about 7 minutes.

According to this method, and regarding national regulations, a fire protection measure should be applied all over the structure to ensure a fire resistance of 30 minutes of ISO curve heating for all its elements.

Method 2

Previous method, based on ISO-834 curve, considers an evolution of smoke temperature that not always represents correctly the expected fire in the analyzed building. First of all, it assumes a unique temperature for the whole fire compartment, which is not true in large compartments, where flashover is not expected to happen. On the other hand it does not account for the fact that fire load is not infinite so that the fire must extinguish at a certain time.

In the present study, the fire design tool TEFINAF based on the expected fire in the building is applied to different scenarios. This allows to compare their effect on the temperature of the steel structure and local temperature distribution.

Different fire scenarios have been analyzed reaching the conclusion that the most aggressive fire for the atrium roof tubular structure is the one prone to happen in the 4th floor.

It is assumed that the most probable fire in this fourth floor would be defined from the following characteristics:

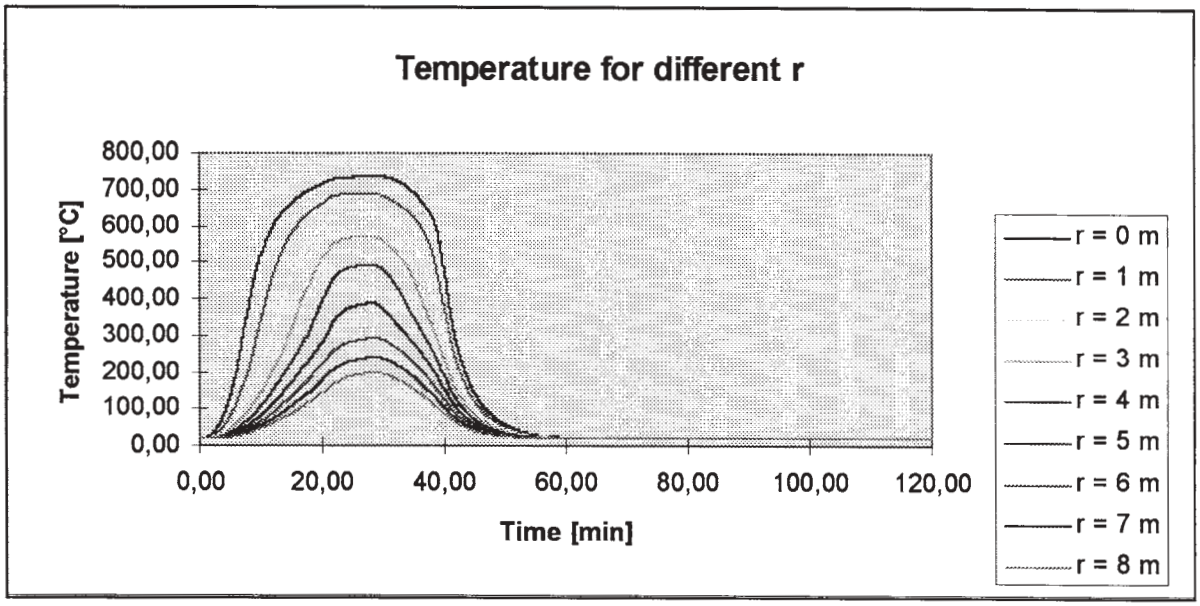
Fire area	36 m^2
Perimeter	24 m
t_α	300s
RHR_{max}	500 kw/m^2
q_f	600 MJ/m^2
Vertical distance from floor to fire	0,5 m

Where t_α is a parameter needed for the definition of the rising phase of the fire curve, RHR_{max} is the maximum rate of heat release and q_f is the expected fire load density in the compartment (see WG3 report).

These parameters allow the definition of the time evolution curve of the rate of heat release. This curve is assumed to be divided in three phases:

-Growing phase : $RHR[kW]=1000(t/t_\alpha)^2$
-Constant phase : RHR_{max}
-Decreasing phase : starts after 70% of the total fire load is burnt.

TEFINAF provides temperature results as a function of the distance from the fire center are shown in the following figure:



From these results it can be deduced that in case fire happens in the fourth storey and assuming a fire of 6m x 6m, the center of the fire is located 3m away from the window, and consequently 3 m away from the roof tubular structure. Maximum temperature reached in the gases three meters away from the fire center is 570°C after 28 minutes, and after 22 minutes a temperature of 550°C is obtained.

Considering the high section factor of the tubular profiles there is almost no difference between gas and steel temperature so the structural elements close to the 4th storey windows would collapse after 22 minutes. If we move away till we are 4 meters from the fire center maximum gas temperature is 490°C, so these elements would never collapse.

5.4 CONCLUSIONS

The presented analysis allows to deduce that only the structural members lying in the area limited by the external perimeter of the roof and the one meter inner from the building inside walls perimeter, must be protected.

According to this study an intumescent paint was applied on the refereed elements of the structure avoiding the use of an over designed structure or the use of intumescent paint on all over the elements.

ANNEX 6

6 OFFICE BUILDING "LANGENTHAL", SWITZERLAND

6.1 INTRODUCTION

This case study describes three methods to quantify the influence of natural fire conditions and active fire protection measures on the structural fire resistance design. For an existing office building the safety levels of two building concepts (e.g. one according to the prescriptive fire regulations and an alternative design) are analysed and compared. For this comparison the following three risk based methods are applied:

- The "Risk Evaluation" method according to **SIA DOC 81** (Gretener Method [1]) is an easy to apply grading method for a rapid risk assessment.
- The **probabilistic NFSC-Method** applies natural fires for a performance based structural fire design. The quantification of active measures on the structural reliability is based on a probabilistic approach.
- The **NFSC-Method** [2] uses the same probabilistic background to fix partial safety factors γ, which can then be used in a deterministic analysis.

This analyse is described in details in the Annex C of the WG5 report.

This summary gives a short overview of the content of this report for hurried readers.

1. INTRODUCTION

Aim, scope and limitations of the described method are mentioned.

2. DESCRIPTION OF THE BUILDING

The architectural design of the existing office building is reviewed providing the building layout, the combustible material, the ventilation conditions and information about the occupancy and the design loads.

3. DESIGN OF REFERENCE SECTIONS AT ROOM TEMPERATURES

For the code complying and for the alternative fire safety design (which has actually been built) the structural system and the section design are reviewed. The deterministic resistance and the failure probability are calculated for cold design.

4. DESIGN OF REFERENCE SECTIONS IN CASE OF FIRE

For the code complying and for an alternative fire safety design the structural system and the section design is reviewed. The deterministic resistance and the failure probability are calculated for fire design.

5. DESCRIPTION OF THE PROBABILISTIC NATURAL FIRE SAFETY CONCEPT

The modelling of the actions and the structural response of a building in a natural fire according the NFSC-Method is explained. The probabilistic method is described showing the procedure, assumptions and background.

6. APPLICATION OF THE PROBABILISTIC NATURAL FIRE SAFETY CONCEPT

The NFSC-Method is applied on the code complying and the alternative building design.

7. SWISS RISK EVALUATION METHOD

It is a grading method based on a large statistical survey. The procedure consists in the verification of a value of a global fire safety factor γ. It is applied to the code conforming and the alternative design.

8. SIMPLIFIED NATURAL FIRE SAFETY CONCEPT

The simplified NFSC method uses partial safety factors γ to analyse the risk levels of the two alternative building concepts. The partial safety factors cover the compartment area, the danger of activation and the benefits of the use of active fire fighting measures.

9. COMPARISON AND CONCLUSION

The results found by applying of the three methods are discussed.

In this annex 6, only the points 1, 2 and 8, which illustrate the application of the NFSC method as defined in this main part, are given.

6.2 DESCRIPTION OF THE BUILDING

6.2.1 Description of the building

The following example is a four storey steel-framed office block in Langenthal in the canton of Berne realised in 1992 [3]. The office building was built for the municipal and district administration.

It is an office block for 200 employees with a total volume of 33.000 m^3. The ground floor area, the two basement floors and the upper three floors include 1.306 m^2 each. The building has a length of 80 m, a width of 20 m and a height of 16 m.

The basement of the building is realised in reinforced concrete and the ground floor up to the 3rd storey by a structural steel frame with pre-stressed concrete slab elements. The round steel columns are located on the outside of the office area and the facade so that an optimal room compartmentation can be achieved.

The office building has no air-conditioning system, the temperature can be regulated by opening and closing the windows.

The fire safety concept includes three smoke resistant fire compartments (each storey with a size of 80 · 20 = 1.600 m^2). One is designed as central open staircase with direct access to a limited number of office rooms. The escape routes are not code-conform but agreed with the Cantonal fire authority (GVB/AIB) and include three glazed escape staircases with an E30 rating (smoke and flame-proof glass, with no resistance against radiation).

Basic normal measures are portable fire extinguisher and indoor hydrants. As a monitoring concept a smoke detection system is installed in the entire building with a first alarm to reception desk located in the building itself. The local public fire brigade (top category class) is located in the immediate vicinity of the building. Besides all this the lightning protection device is sufficient.

The structural fire resistance for the two basement storeys is R60. The steel columns at the outside as well as the inner solid or composite steel columns are not protected and are rated R30. The inner steel beams are protected with an intumescent paint to reach R30.

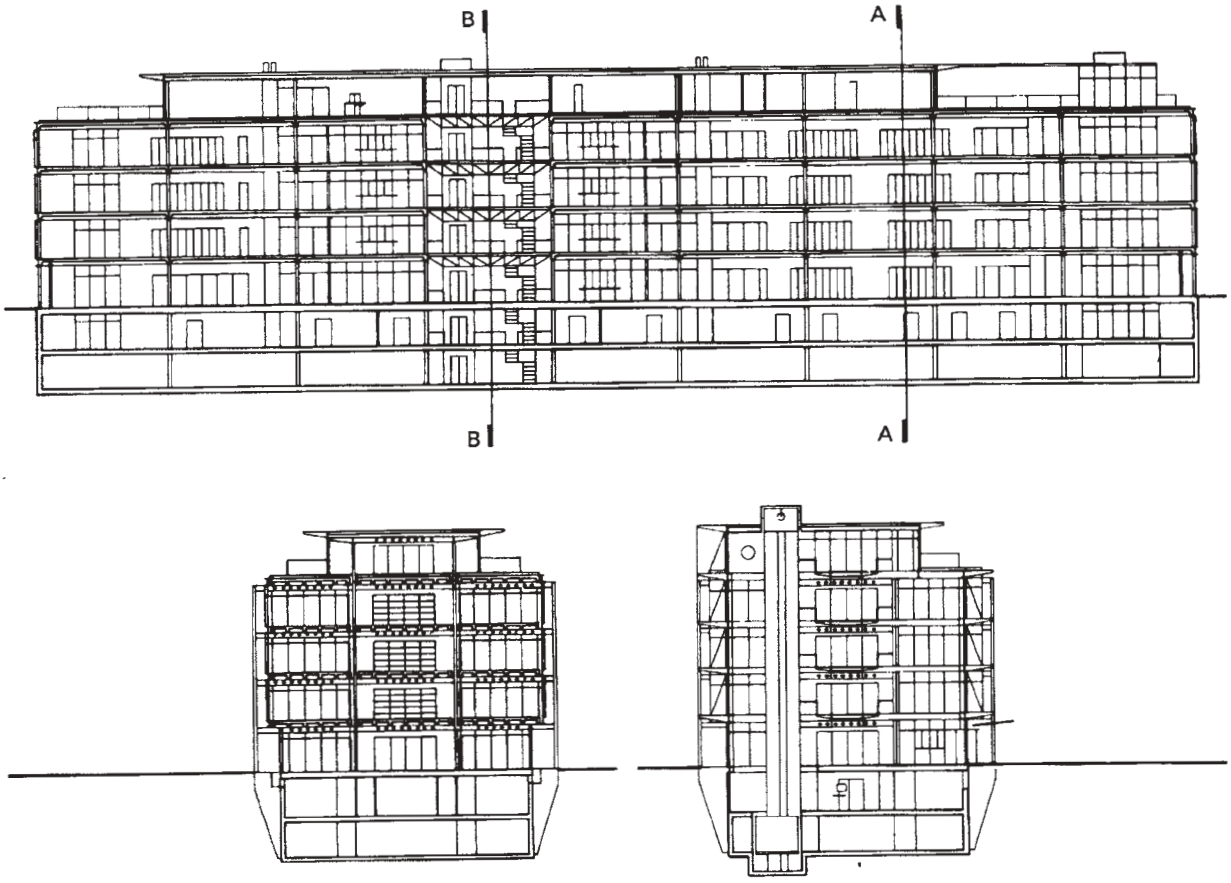
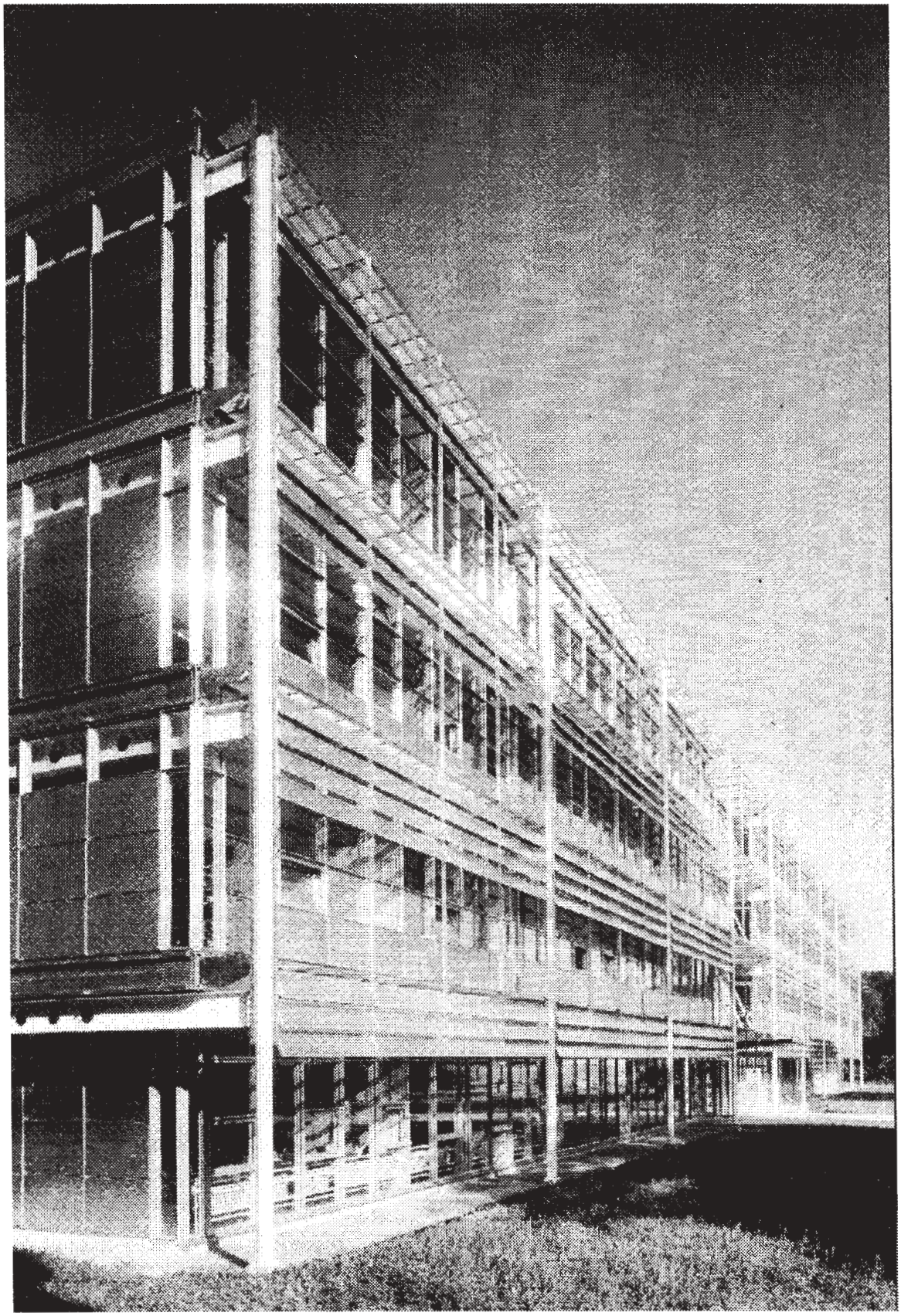


Figure 6.1: Four storey steel frame office building



Picture 6.1: Office building Langenthal

6.2.2 Structural system and loads

The structure consists of a braced steel frame with continuous 6,66 m span steel beams (IPE 400) and 3,20 m long continuous steel columns (ROR ⌀ 298,5 mm, t = 20 mm[1]) with the following loads:

Self weight: Steel beam IPE 400 g = 0,66 kN/m
Concrete slab element g = 2,5 kN/m^2
(d = 10 cm)
60 mm cement coating g = 1,2 kN/m^2
15 mm surface coating g = 0,3 kN/m^2
g_{tot}= 4,66 kN/m^2
b = 8,88 m
G_B= 41,4 kN/m

Steel column ROR ⌀ 298,5 g = 1,37 kN/m
(t = 20 mm)
g_{tot}= 1,37 kN/m^2
ℓ = 3,20 m
G_C= 4,3 kN

Imposed load: Office building (code of action SIA 160 [4]: category B)
$q_{general}$= 3,0 kN/m^2
b = 8,88 m
N_B= 26,6 kN/m

Snow load h = 476 m

$$s = \left[1 + \left(\frac{476}{350}\right)^2\right] \cdot 0{,}4\,\mathrm{kN/m^2} = 1{,}14\,\mathrm{kN/m^2}$$

$$S = \xi \cdot s = 0{,}8 \cdot 1{,}14\,\mathrm{kN/m^2} = 0{,}91\,\mathrm{kN/m^2}$$

6.2.3 Room characteristics

For the case study two room geometry's have been analysed and will be compared:

- The first corresponds to the **code design**, which would have been built according the national prescriptive regulations [5] (see Figure 6.2).
- The alternative and **existing design** which has actually been built in Langenthal represents an attempt to reach the same risk level as by the code design but with less structural measures and considering active fire fighting measures (see Figure 6.3).

[1] Note: In the existing building solid columns ⌀ 177.8 mm are used. These columns reach a fire resistance of about 45 minutes i.e. more than the required 30 minutes. Therefore in the example ROR ⌀ 298.5 mm, t = 20 mm sections were used having a fire resistance of about 30 minutes as required.

6.2.3.1 Code design

The code design [5] allows 600 m^2 maximum office space without active measures and requires a resistance R60 of the structural elements. Therefore the design office room was taken as part of the storey (fire compartment size of 20 m · 30 m) with windows on three sides.

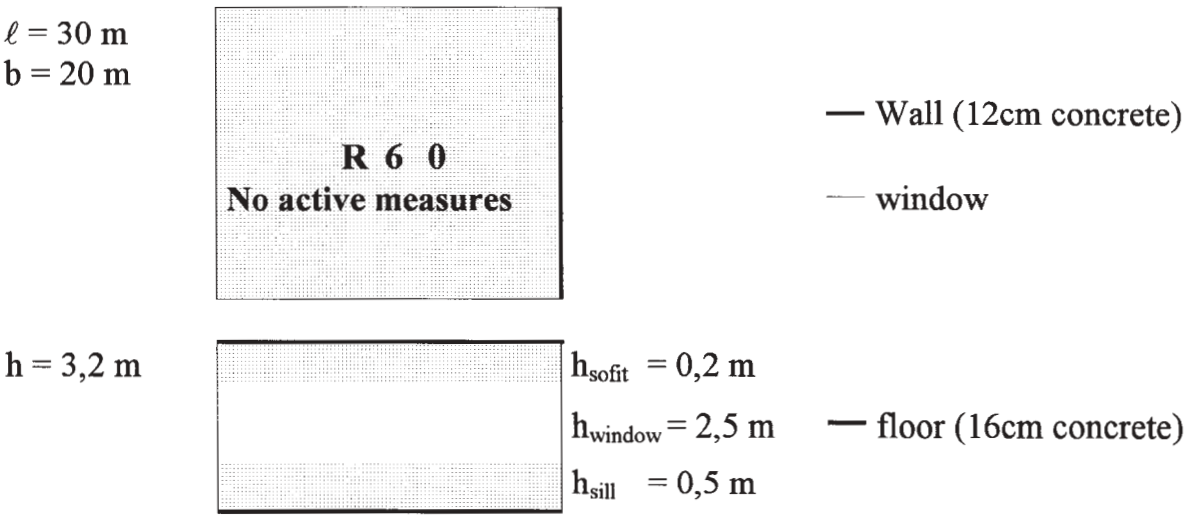


Figure 6.2: Room and ventilation characteristics for small office (20m · 30m)

6.2.3.2 Existing design

The existing design has no compartmentation and a fire resistance R30 of the structure. Therefore the design office was taken as the whole storey (fire compartment size of 20 m · 80 m) with windows on four sides.

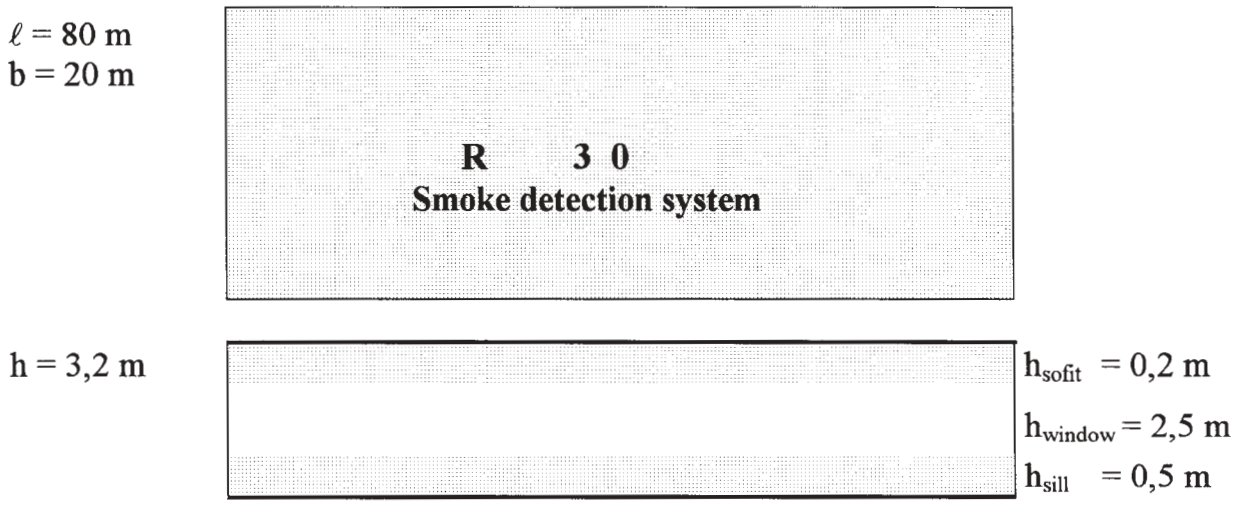


Figure 6.3: Room and ventilation characteristics for large office (20m · 80m)

These room characteristics were used as input data for the parametric design fire studies with the BSBG one zone fire simulation program [6] (see chapter 6.3.4).

6.3 Application of the simplified NFSC-Method to the building according to the code design

Global safety index: $\gamma_{q,f} = \gamma_{q,1} \cdot \gamma_{q,2} \cdot \gamma_{ni} = 1{,}28 \cdot 1{,}0 \cdot 1{,}0 = 1{,}28$

Compartment:	$\gamma_{q,1}$	=	1,28	$A = 30\ m \cdot 20\ m = 600\ m^2$
Danger of activation:	$\gamma_{q,2}$	=	1,0	normal risk
Fire fighting	γ_{ni}	=	1,0	no special active measures

Design fire load:

$\mathbf{q_{f,d} = \gamma_{q,f} \cdot q_{f,char} = 1{,}28 \cdot 570{,}0\ MJ/m^2 = 730\ MJ/m^2}$

$q_{f,d}$: design fire load

$q_{f,char} = 570\ MJ/m^2$ characteristic value of the fire load (80% fractile)

The one-zone fire simulation program BSBG [6] was used to calculate the time temperature curve with the following parameters:

Fire load density: $q_{d,\,fire} = 730\ MJ/m^2$

Max. RHR: $\dot{q}_{d,\,fire} = 320\ \frac{kW}{m^2}$

Fire spread: $v = 0{,}5$ m/min (in each direction starting from the middle of the room)

Combustion ratio: $5\ \frac{kg_{air}}{kg_{wood}}$

The maximum steel temperature reaches $\theta_{max} = 422$ °C for the R60 beam and $\theta_{max} = 398$ °C for the R60 column. By comparing the maximum steel temperature θ_{max} with the critical temperature (see chapter 4.2 of Annex C of the WG5 report) one can verify that in both cases no collapse will occur for the design fire load.

Beam R60:	$\theta_{max} = 422$ °	<	$\theta_{crit} = 602{,}5$ °C
Column R60:	$\theta_{max} = 398$ °C	<	$\theta_{crit} = 630{,}0$ °C

6.4 Application of the simplified NFSC-Method to the building according to the existing design

Global safety index: $\gamma_{q,f} = \gamma_{q,1} \cdot \gamma_{q,2} \cdot \gamma_{ni} = 1{,}4 \cdot 1{,}0 \cdot 0{,}72 = 1{,}0$

Compartment:	$\gamma_{q,1}$	=	1,4	$A = 80\ m \cdot 20\ m = 1.600\ m^2$
Danger of activation:	$\gamma_{q,2}$	=	1,0	normal risk
Fire fighting	γ_{ni}	=	$0{,}80 \cdot 0{,}90 = 0{,}72$	automatic detection system

Design fire load:

$q_{f,d} = \gamma_{q,f} \cdot q_{f,char} = 1{,}0 \cdot 570{,}0\ MJ/m^2 = \mathbf{570\ MJ/m^2}$

$q_{f,d}$: design fire load

$q_{f,char} = 570\ MJ/m^2$ characteristic value of the fire load (80% fractile) (based on a previous version of the WG3 report)

The one-zone fire simulation program BSBG [6] was used to calculate the time temperature curve with the following parameters:

Fire load density: $q_{d,fire} = 570\ MJ/m^2$

Max. RHR: $\dot{q}_{d,fire} = 320\ \frac{kW}{m^2}$

Fire spread: $v = 0{,}5$ m/min(in each direction starting from the middle of the room)

Combustion ratio: $5\ \frac{kg_{air}}{kg_{wood}}$

The maximum steel temperature was $\theta_{max} = 485$ °C for the R30 beam and $\theta_{max} = 525$ °C for the R30 column.

By comparing the maximum steel temperature θ_{max} with the critical temperature (see chapter 4.2 of the Annex C of the WG5 report) one can verify that in both cases no collapse will occur for the design fire load.

Beam R30: $\theta_{max} = 485$ °C $<$ $\theta_{crit} = 602{,}5$ °C

Column R30: $\theta_{max} = 525$ °C $<$ $\theta_{crit} = 630{,}0$ °C

CONCLUSIONS

The analysis of the structural fire safety level of the two design concepts for an existing office building in Langenthal Switzerland (code design R60, maximum size of the compartment ≤ 600 m^2; alternative design R30, maximum size of the compartment 1.600 m^2, which was actually built) was performed.

The analyse shows an acceptable safety level for both design concepts with a slightly higher structural reliability of the code complying concept. However the natural fire safety concept concentrates only on the influence of active fire protection on the structural fire resistance. Further benefits of active measures for life safety are not taken into consideration at present.

Nevertheless this concept allow for new flexibility in fire safety design of buildings by recognising the interaction between active and structural fire safety measures. This can lead to considerable savings for steel and composite structures without reducing the fire safety level.

REFERENCES

[1] SIA DOC 81: **Brandrisikobewertung**, SIA, Zürich 1984

[2] Cajot L.-G. et al.: **WG 5: Methodology to Deduce from the Probability Data the "Design Natural Fire Curve"**, NFSC WG 5, Final report, 1st draft, Esch-Alzette, January 1999

[3] Bauen in Stahl: **Verwaltungszentrum Langenthal**, SZS, Issue 16, 1994

[4] SIA 160: **Einwirkungen auf Tragwerke**, Schweizer Ingenieur- und Architektenverein, Zürich 1989

[5] VKF: **Brandschutzvorschriften**, Vereinigung Kantonaler Feuerversicherungen, Bern 1993

[6] Frangi T. et al.: **BSBG**, Geilinger AG, März 1990

ANNEX 7

7 COMPLEX "GEESSEKNAEPPCHEN" : LYCEE (LOT L), LUXEMBOURG

In Luxemburg, we have applied the method to the steel parts of the structure of 5 buildings of the complex "Geesseknäppchen" which is composed of a swimming pool, a sport hall, a forum and two schools. All the fire safety calculations concerning the 5 buildings are described in a report [288]. Only one example concerning one of the school called "lycée (Lot L)" is given here.

FIRE SCENARIO: **"ELECTROTECHNIC ROOM" fully engulfed by fire (OZONE Calculation)**

General

Mean Height = 3 m Profile: IPE 400 $(\frac{A_m}{V} = 152\ m^{-1})$

Fire area A_{fi} = 153 m²
Volume = 459 m³

Assumptions

- Uniform equivalent fire load

  $q_{k,f}$ = 410 MJ / m²
  (school see page D : Office / Technical)

  m = 0,8
  γ_{q1} = 1,00 + 0,25 (128/225) = 1,14
  γ_{q2} = 1,2 (page B : Machinery)

  No sprinkler at all but SFB (Standard Fire Brigade)
  ADS (Automatic Detection System)
  and AAT (Automatic Alarm Transmission)

$\gamma_n = \gamma^{SFB} . \gamma^{ADS} . \gamma^{AAT} = 0,73 * 0,8 * 0,9$
$= 0,53$

$q_{f,d}$ = 410*0,8*(1,14*1,2*0,53)
= 236 MJ /m²

Areas:

- $A_{floor} \approx 10\ m \times 15{,}3\ m = 153\ m^2$
- $A_{ceiling} \approx 10\ m \times 15{,}3\ m = 153\ m^2$
- $A_{walls} \approx 3\ m * (10 + 10 + 15{,}3) + 1m * 15{,}3 = 121{,}2\ m^2$
- $A_{windows} \approx 2\ m * 15{,}3\ m = 30{,}6\ m^2$

Openings:

The doors are considered as closed, for that reason, we don't take into account that value for our calculation. The total area of windows is 30,6 m² which are broken by the heating according to the following steps:

$\Omega_{windows} = 30{,}6\ m^2$
$\Omega_{broken\ windows}(20°C)$: 5% of 30,6 m² = 1,53 m²
$\Omega_{broken\ windows}(300°C)$: 75% of 30,6 m² = 23 m²
$\Omega_{broken\ windows}(500°C)$: 100% of 30,6 m² = 30,6 m²

Results

Time in min	T°_{air}	T°_{steel}
30'	271°	160°
60'	321°	456°
	$T^{\circ max}_{air}$	$T^{\circ max}_{steel}$
50'	**584°**	-
55'	-	**499°**

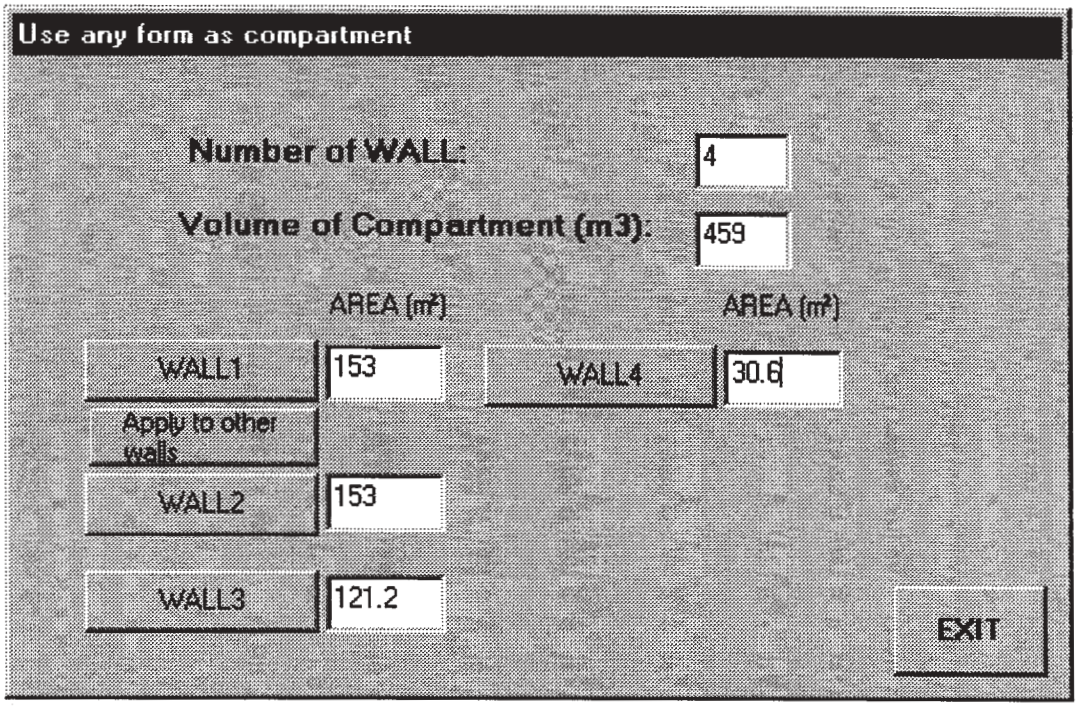
Conclusions:

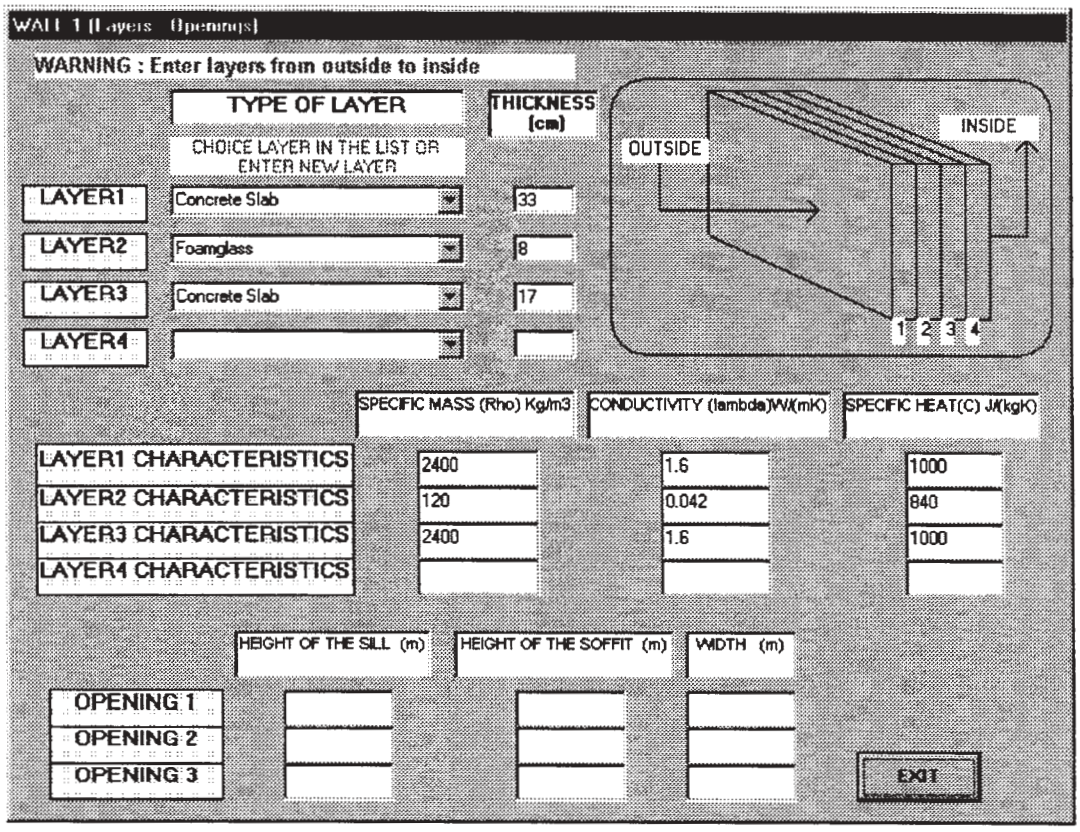
The fire curve is given on page 173. It has been provided by the program OZONE (see WG1 report). The pages 169 to 172 show the data of the OZONE calculation. The $T^{\circ max}_{steel}$ at 55' is 499°C. The structure submitted to this fire curve is simulated by the CEFICOSS program (see pages 174 to 181). This simulation shows that the stability of the frame is insured providing that the steel beams are connected to the concrete slab (composite section) and that the following active measures are respected:

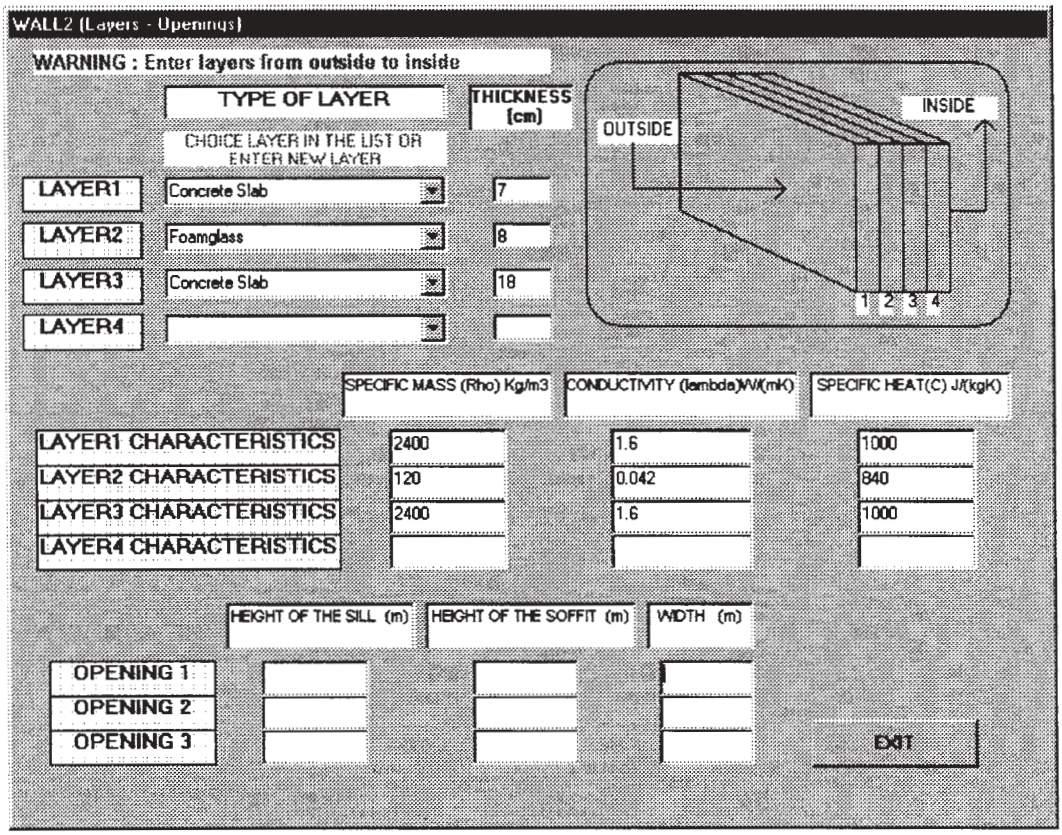
- **Automatic fire detection by smoke**
- **Automatic alarm transmission to fire brigade**

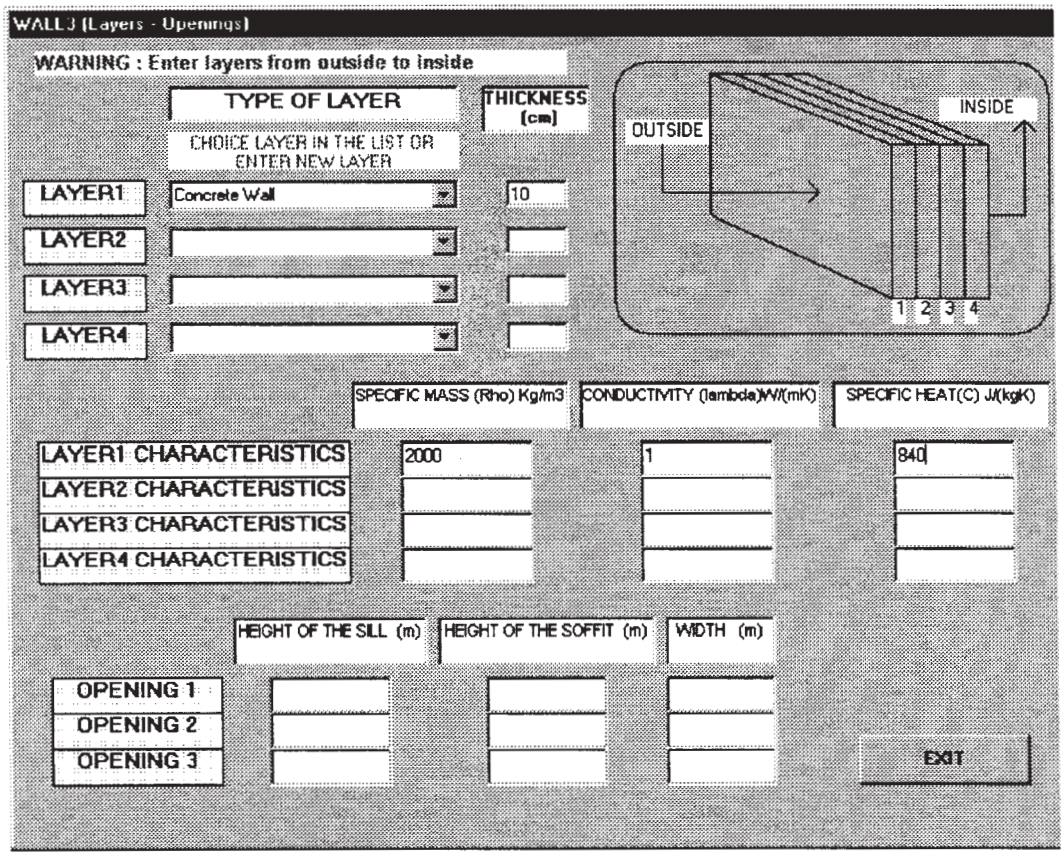
Due to the beam deflection in case of fire, the beam get shorter of about 5 cm. A sufficient support length needs to be foreseen to avoid the slip outside the support.

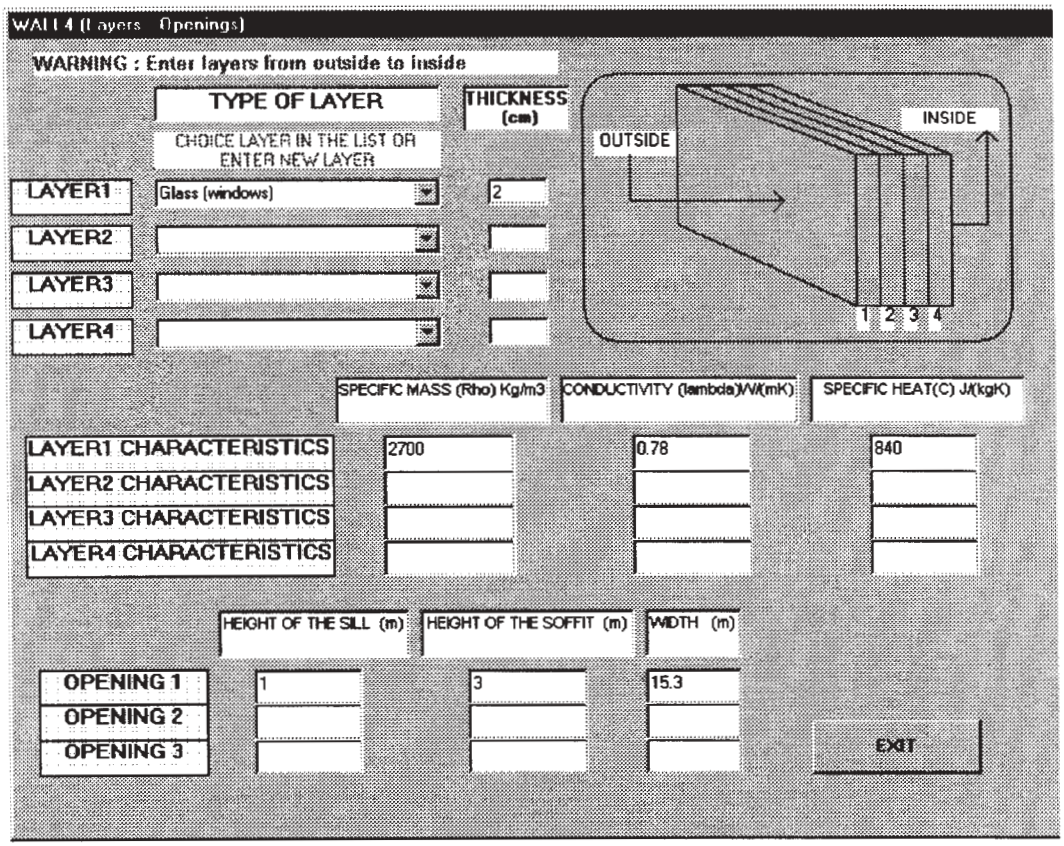
Scenario V– LYCEE –
A_{fi} = 153 m² - (OZONE calculation)
Ventilation in function of the time

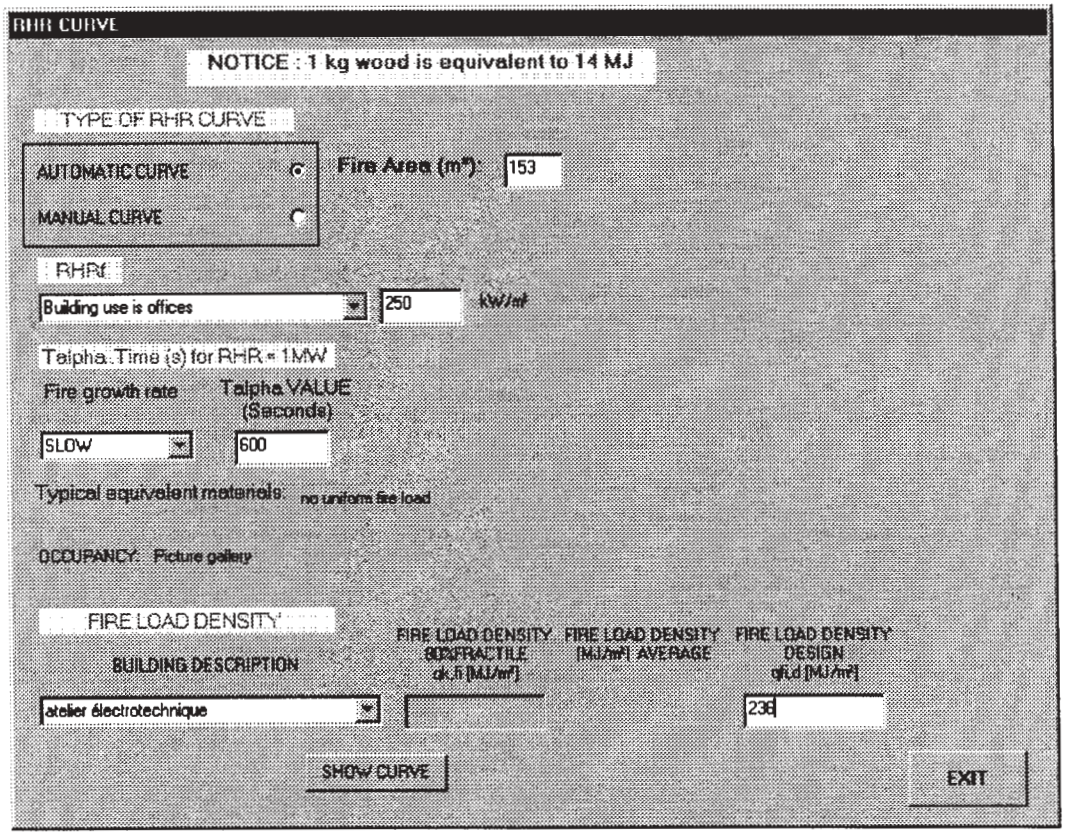


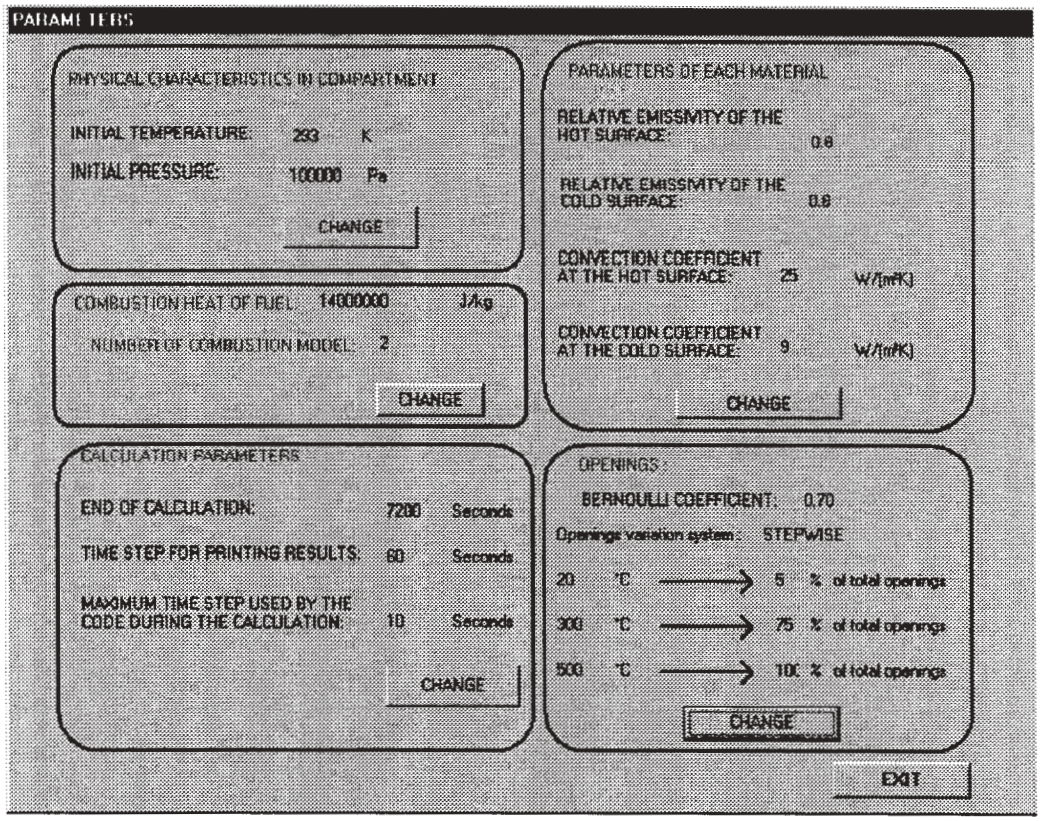


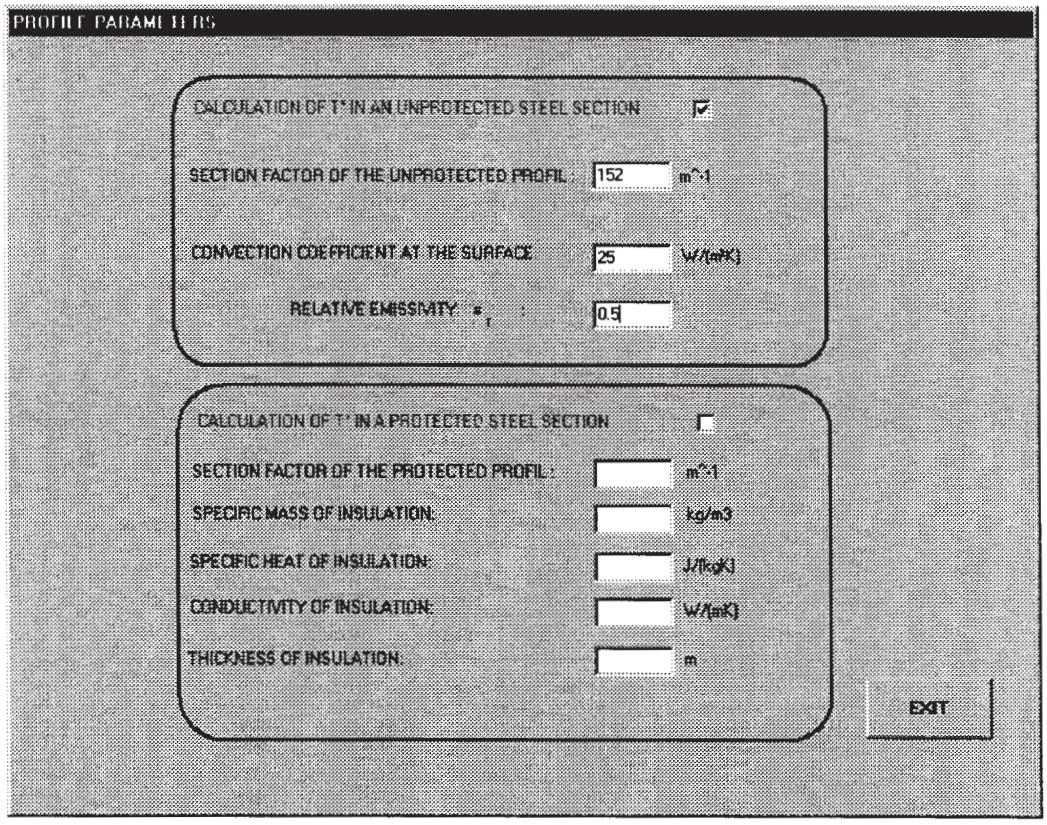

WALL2 (Layers - Openings)
WARNING : Enter layers from outside to inside
TYPE OF LAYER
CHOICE LAYER IN THE LIST OR ENTER NEW LAYER
THICKNESS (cm)
LAYER1
Concrete Slab
7
LAYER2
Foamglass
8
LAYER3
Concrete Slab
18
LAYER4
OUTSIDE
INSIDE
1 2 3 4
SPECIFIC MASS (Rho) Kg/m3
CONDUCTIVITY (lambda)W/(mK)
SPECIFIC HEAT(C) J/(kgK)
LAYER1 CHARACTERISTICS
2400
1.6
1000
LAYER2 CHARACTERISTICS
120
0.042
840
LAYER3 CHARACTERISTICS
2400
1.6
1000
LAYER4 CHARACTERISTICS
HEIGHT OF THE SILL (m)
HEIGHT OF THE SOFFIT (m)
WIDTH (m)
OPENING 1
OPENING 2
OPENING 3
EXIT


WALL3 (Layers - Openings)
WARNING : Enter layers from outside to inside
TYPE OF LAYER
CHOICE LAYER IN THE LIST OR ENTER NEW LAYER
THICKNESS (cm)
LAYER1
Concrete Wall
10
LAYER2
LAYER3
LAYER4
OUTSIDE
INSIDE
1 2 3 4
SPECIFIC MASS (Rho) Kg/m3
CONDUCTIVITY (lambda)W/(mK)
SPECIFIC HEAT(C) J/(kgK)
LAYER1 CHARACTERISTICS
2000
1
840
LAYER2 CHARACTERISTICS
LAYER3 CHARACTERISTICS
LAYER4 CHARACTERISTICS
HEIGHT OF THE SILL (m)
HEIGHT OF THE SOFFIT (m)
WIDTH (m)
OPENING 1
OPENING 2
OPENING 3
EXIT


WALL 4 (Layers Openings)
WARNING : Enter layers from outside to inside
TYPE OF LAYER
CHOICE LAYER IN THE LIST OR ENTER NEW LAYER
THICKNESS (cm)
OUTSIDE
INSIDE
1 2 3 4
LAYER1
Glass (windows)
2
LAYER2
LAYER3
LAYER4
SPECIFIC MASS (Rho) Kg/m3
CONDUCTIVITY (lambda)W/(mK)
SPECIFIC HEAT(C) J/(kgK)
LAYER1 CHARACTERISTICS
LAYER2 CHARACTERISTICS
LAYER3 CHARACTERISTICS
LAYER4 CHARACTERISTICS
2700
0.78
840
HEIGHT OF THE SILL (m)
HEIGHT OF THE SOFFIT (m)
WIDTH (m)
OPENING 1
OPENING 2
OPENING 3
1
3
15.3
EXIT


RHR CURVE
NOTICE : 1 kg wood is equivalent to 14 MJ
TYPE OF RHR CURVE
AUTOMATIC CURVE
MANUAL CURVE
Fire Area (m²):
153
RHRf
Building use is offices
250
kW/m²
Talpha.Time (s) for RHR = 1MW
Fire growth rate
Talpha VALUE (Seconds)
SLOW
600
Typical equivalent materials:
no uniform fire load
OCCUPANCY: Picture gallery
FIRE LOAD DENSITY
BUILDING DESCRIPTION
FIRE LOAD DENSITY 80%FRACTILE qk,fi [MJ/m²]
FIRE LOAD DENSITY [MJ/m²] AVERAGE
FIRE LOAD DENSITY DESIGN qf,d [MJ/m²]
atelier électrotechnique
236
SHOW CURVE
EXIT

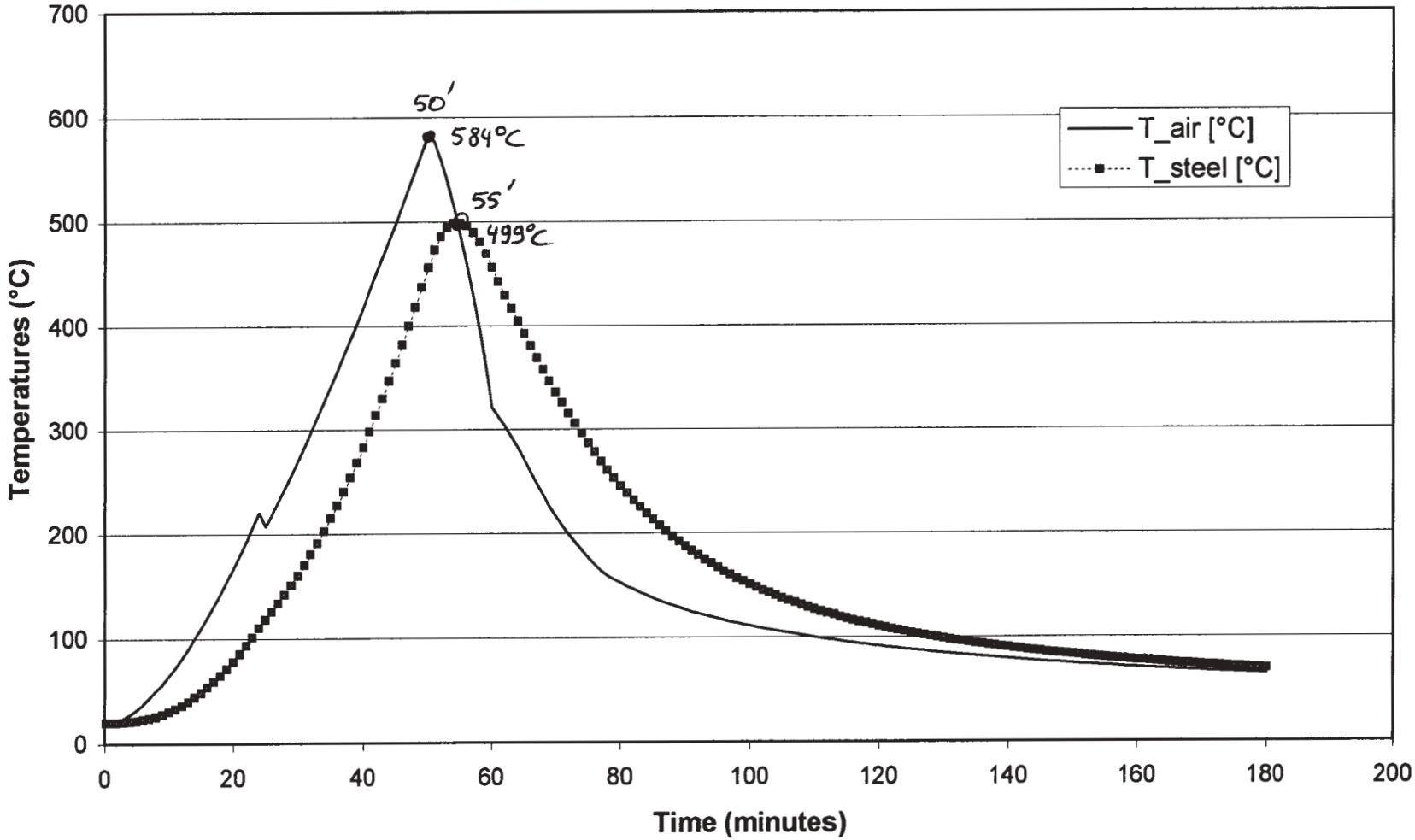

PARAMETERS
PHYSICAL CHARACTERISTICS IN COMPARTMENT
INITIAL TEMPERATURE: 293 K
INITIAL PRESSURE: 100000 Pa
CHANGE
COMBUSTION HEAT OF FUEL: 14000000 J/kg
NUMBER OF COMBUSTION MODEL: 2
CHANGE
CALCULATION PARAMETERS
END OF CALCULATION: 7200 Seconds
TIME STEP FOR PRINTING RESULTS: 60 Seconds
MAXIMUM TIME STEP USED BY THE CODE DURING THE CALCULATION: 10 Seconds
CHANGE
PARAMETERS OF EACH MATERIAL
RELATIVE EMISSIVITY OF THE HOT SURFACE: 0.8
RELATIVE EMISSIVITY OF THE COLD SURFACE: 0.8
CONVECTION COEFFICIENT AT THE HOT SURFACE: 25 W/(m²K)
CONVECTION COEFFICIENT AT THE COLD SURFACE: 9 W/(m²K)
CHANGE
OPENINGS :
BERNOULLI COEFFICIENT: 0.70
Openings variation system : STEPWISE
20 °C → 5 % of total openings
300 °C → 75 % of total openings
500 °C → 100 % of total openings
CHANGE
EXIT


PROFILE PARAMETERS
CALCULATION OF T° IN AN UNPROTECTED STEEL SECTION
SECTION FACTOR OF THE UNPROTECTED PROFIL : 152 m^-1
CONVECTION COEFFICIENT AT THE SURFACE : 25 W/(m²K)
RELATIVE EMISSIVITY : 0.5
CALCULATION OF T° IN A PROTECTED STEEL SECTION
SECTION FACTOR OF THE PROTECTED PROFIL : m^-1
SPECIFIC MASS OF INSULATION: kg/m3
SPECIFIC HEAT OF INSULATION: J/(kgK)
CONDUCTIVITY OF INSULATION: W/(mK)
THICKNESS OF INSULATION: m
EXIT

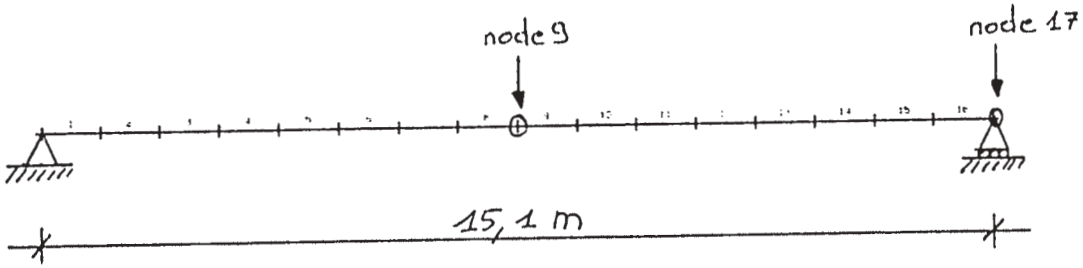
Scenario V. - LYCEE (Lot L)

Temperatures in the air and in the steel (IPE 400)

Broken windows in function of the time



LYCEE (LOT L) GEESSEKNAPPCHEN
ELEMENTS OF THE STRUCTURE



Scale of the structure : 1 / 100

ARBED-RECHERCHES / RPS DEPARTMENT	CEFICOSS Analysis / CEF12.0
PROJECT TITLE LYCEE (LOT L)	PROJECT NUMBER GEESSEKNAEPPCHEN
	ESCH/ALZETTE : 24-MAR-1999 — SHEET :

LYCEE (LOT L) GEESSEKNAPPCHEN
LOADING OF THE STRUCTURE

DISTRIBUTED LOADS

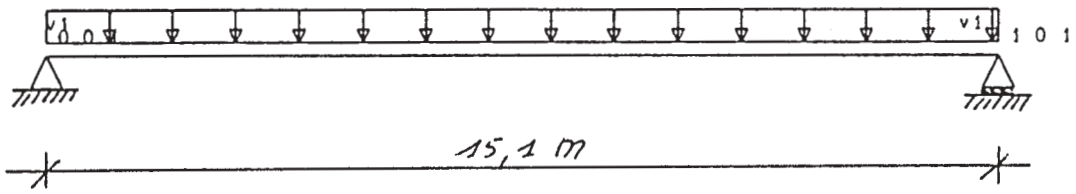
VERTICAL LOADS

v 1 = 11.90 kN/m

$= g + 0{,}5q$

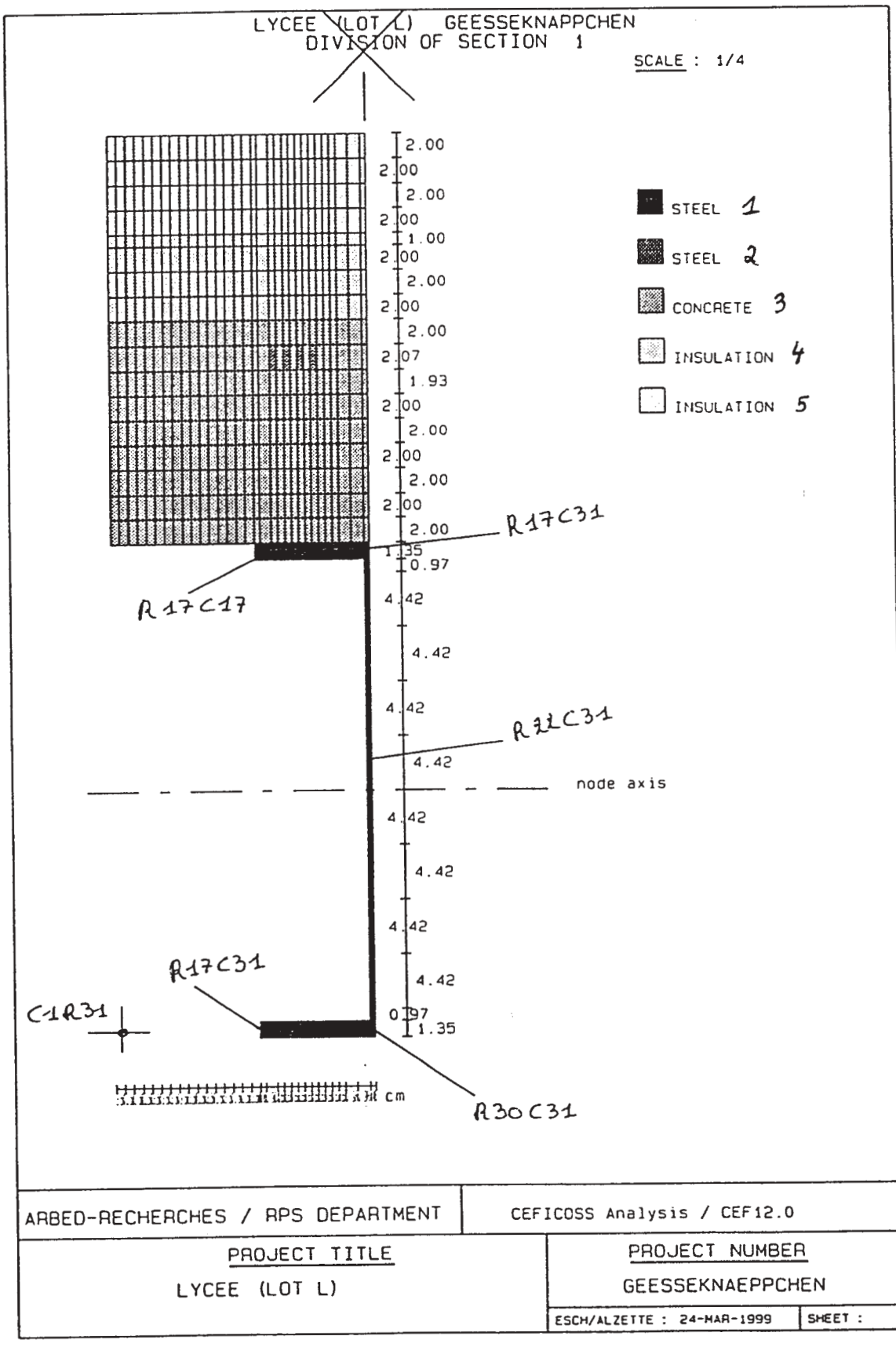
$= (6{,}11 \cdot 1{,}3) + 0{,}5(5 \times 1{,}3) + 0{,}66$

$= 11{,}85$ kN/m



Scale of the structure : 1 / 100

ARBED-RECHERCHES / RPS DEPARTMENT	CEFICOSS Analysis / CEF12.0
PROJECT TITLE LYCEE (LOT L)	PROJECT NUMBER GEESSEKNAEPPCHEN
	ESCH/ALZETTE : 24-MAR-1999 | SHEET :



ARBED-RECHERCHES / RPS DEPARTMENT	CEFICOSS Analysis / CEF12.0
PROJECT TITLE LYCEE (LOT L)	PROJECT NUMBER GEESSEKNAEPPCHEN
	ESCH/ALZETTE : 24-MAR-1999 | SHEET :

THERMAL CONDITIONS

THERMAL LAWS OF STEEL AND CONCRETE ACCORDING TO EC4 PART 10 AND BSC FOR Ca

STEEL 1
- Resultant emissivity = 0.30
- Coefficient of convection cold = 9.000 W/m2K
- Coefficient of convection hot = 25.000 W/m2K

STEEL 2
- Resultant emissivity = 0.50
- Coefficient of convection cold = 9.000 W/m2K
- Coefficient of convection hot = 25.000 W/m2K

CONCRETE 3
- Resultant emissivity = 0.30
- Coefficient of convection cold = 9.000 W/m2K
- Coefficient of convection hot = 25.000 W/m2K

THERMAL LAWS OF SECOND ORDER FOR INSULATION MATERIALS

INSULATION 4
- Thermal conductivity = 0.042
- Specific heat = 840.000
- Resultant emissivity = 0.50
- Coefficient of convection cold = 9.000 W/m2K
- Coefficient of convection hot = 25.000 W/m2K

INSULATION 5
- Thermal conductivity = 2.000-0.240*(T/100)+0.012*(T/100)2
- Specific heat = 900.000+80.000*(T/100)-4.000*(T/100)2
- Resultant emissivity = 0.50
- Coefficient of convection cold = 9.000 W/m2K
- Coefficient of convection hot = 25.000 W/m2K

WATER CONTENTS

- Water content 1 = 40.000 l/m3

MECHANICAL PROPERTIES

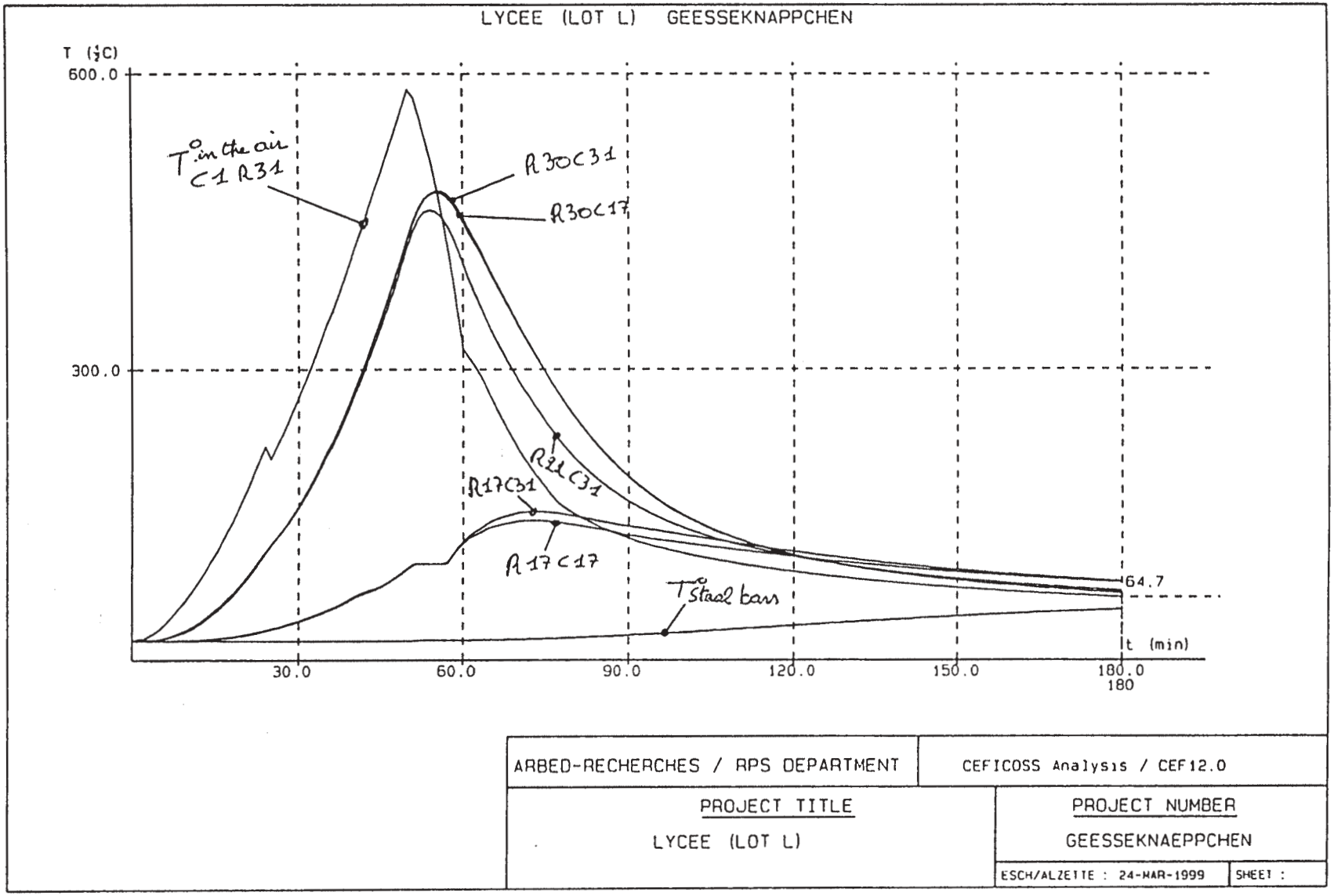
STEEL LAW ACCORDING TO EC4 PART 10 WITH STRAIN HARDENING

STEEL 1
- Yield point = 35.500 kN/cm2

STEEL 2
- Yield point = 50.000 kN/cm2

CONCRETE LAW ACCORDING TO EC4 PART 10

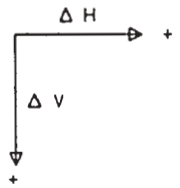
CONCRETE 3
- Compressive strength = 2.905 kN/cm2

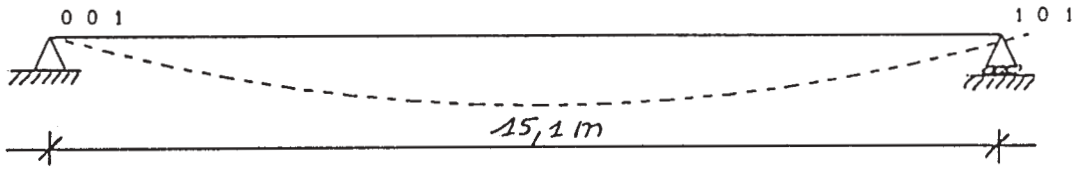

LYCEE (LOT L) GEESSEKNAPPCHEN
T (°C)
600.0
300.0
T°in the air C1 R31
R30C31
R30C17
R21C31
R17C31
R17C17
T°steel bars
64.7
t (min)
30.0
60.0
90.0
120.0
150.0
180.0
180
ARBED-RECHERCHES / RPS DEPARTMENT
CEFICOSS Analysis / CEF12.0
PROJECT TITLE
LYCEE (LOT L)
PROJECT NUMBER
GEESSEKNAEPPCHEN
ESCH/ALZETTE : 24-MAR-1999
SHEET :

LYCEE (LOT L) GEESSEKNAPPCHEN
DISPLACEMENT OF THE STRUCTURE AFTER 55.00 MINUTES

Maximum displacement

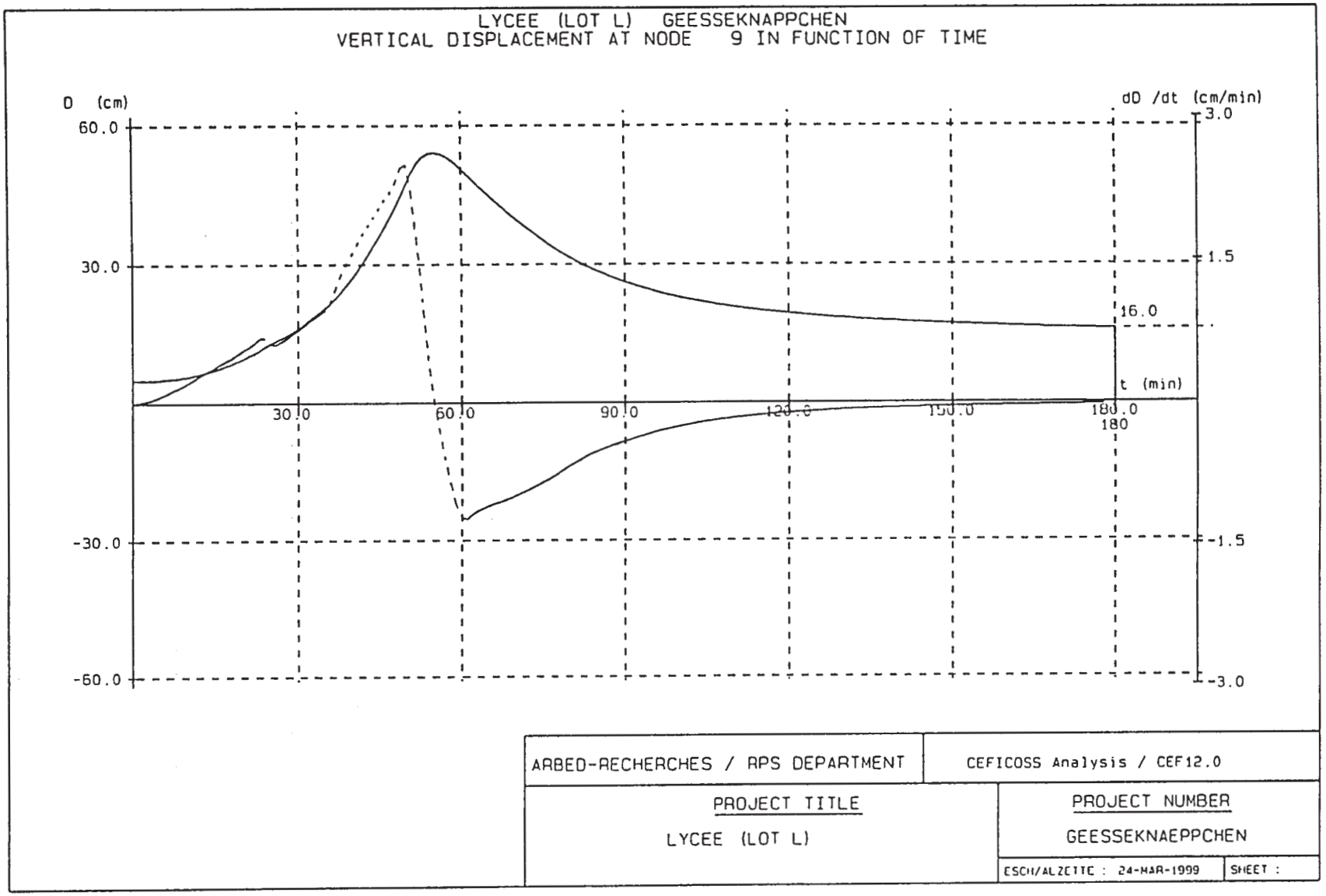
Horizontal :	4.793 cm
Vertical :	54.161 cm

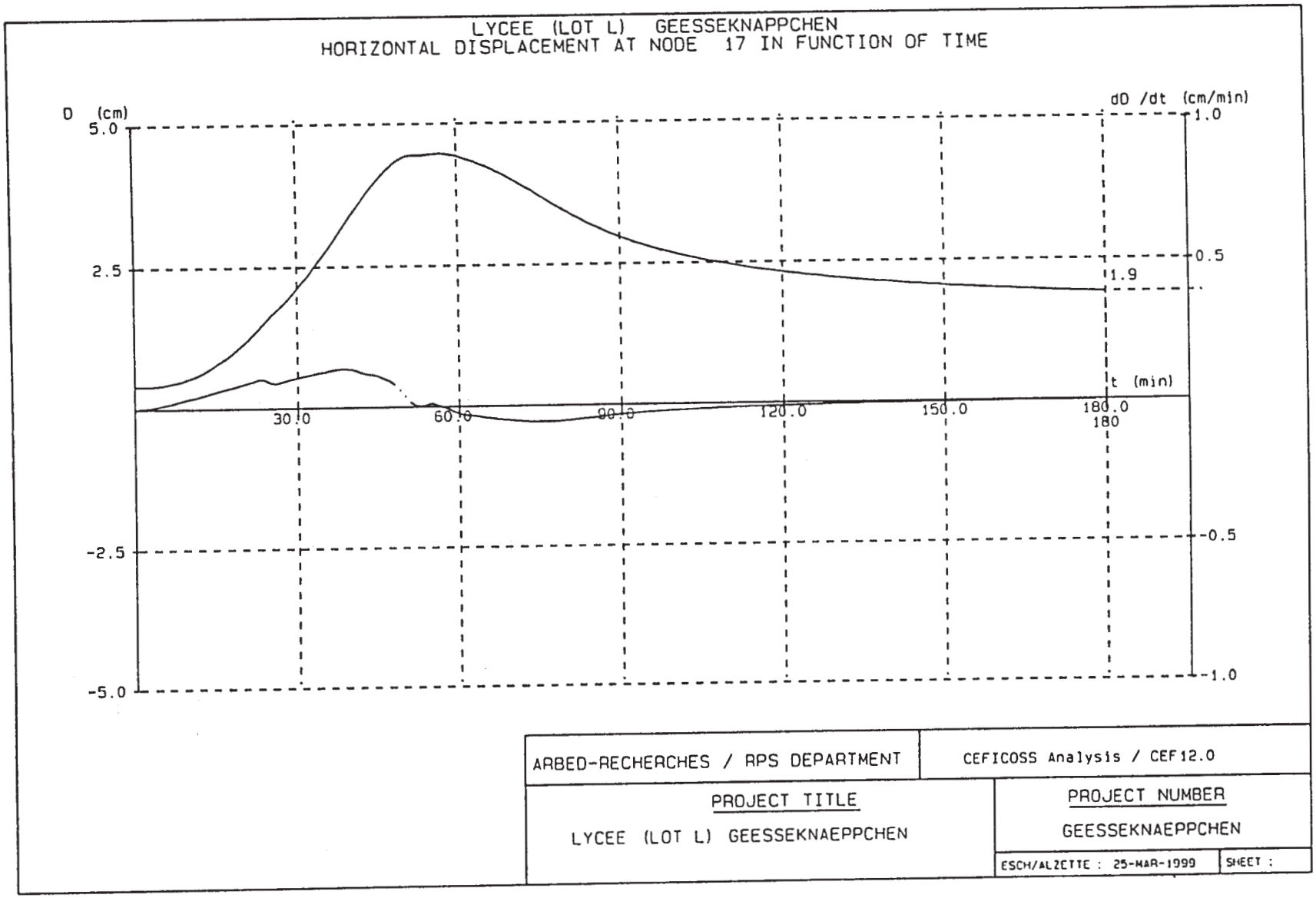




Scale of vertical displacements : 1 /50
Scale of horizontal displacements : 1 /10
Scale of the structure : 1 / 100

ARBED-RECHERCHES / RPS DEPARTMENT	CEFICOSS Analysis / CEF12.0
PROJECT TITLE LYCEE (LOT L)	PROJECT NUMBER GEESSEKNAEPPCHEN
ESCH/ALZETTE : 24-MAR-1999	SHEET :


LYCEE (LOT L) GEESSEKNAPPCHEN
VERTICAL DISPLACEMENT AT NODE 9 IN FUNCTION OF TIME
D (cm)
dD /dt (cm/min)
60.0
30.0
-30.0
-60.0
3.0
1.5
-1.5
-3.0
16.0
t (min)
30.0
60.0
90.0
120.0
150.0
180.0
180
ARBED-RECHERCHES / RPS DEPARTMENT
CEFICOSS Analysis / CEF12.0
PROJECT TITLE
LYCEE (LOT L)
PROJECT NUMBER
GEESSEKNAEPPCHEN
ESCH/ALZETTE : 24-MAR-1999
SHEET :


LYCEE (LOT L) GEESSEKNAPPCHEN
HORIZONTAL DISPLACEMENT AT NODE 17 IN FUNCTION OF TIME
D (cm)
5.0
2.5
-2.5
-5.0
dD /dt (cm/min)
1.0
0.5
1.9
-0.5
-1.0
t (min)
30.0
60.0
90.0
120.0
150.0
180.0
180
ARBED-RECHERCHES / RPS DEPARTMENT
CEFICOSS Analysis / CEF12.0
PROJECT TITLE
LYCEE (LOT L) GEESSEKNAEPPCHEN
PROJECT NUMBER
GEESSEKNAEPPCHEN
ESCH/ALZETTE : 25-MAR-1999
SHEET :

II. WORKING GROUP 1

NATURAL FIRE MODELS

1 GAS TEMPERATURE IN A FIRE COMPARTMENT SUMMARY OF THE DIFFERENT CALCULATION METHODS

1.1 INTRODUCTION: ELEMENTS ON THE DEVELOPMENT OF FIRE IN BUILDINGS

A fire occurs when three elements are brought together: a heat source, oxygen and fuel.

Concerning its development in time, a fire can be divided in several phases, see Figure 1.1.

1. The first one is the **ignition** of the fire, usually at a point source. The temperatures in the gases are small and have no influence on the structure.
2. Then comes the **propagation** phase, during which the fire spreads from objects to objects, by radiation or by direct contact. The temperatures rise in the compartment and, from here, the situation can evolve towards one of the 2 following possibilities.
   - Either the temperature of the gases become so elevated – around 500°C - that, after a certain period of time, it causes the sudden ignition of every objet in the compartment. This phenomenon is called the ***flashover***. There is a fully engulfed fire.
   - Or there is no spread of the fire to the whole compartment, because the propagation is so slow that the temperature rise is not sufficient to cause the flashover, or because the fire can find no combustible material in its close vicinity. The fire remains **localised**.
3. In the next period, the fire is **fully developed** and keeps on burning at a rather constant rate, leading to very small variations of the temperatures.
4. The last phase is the **cooling** phase. During this phase the mean temperature may remain rather high during a certain time and the influence on the structure can be important.

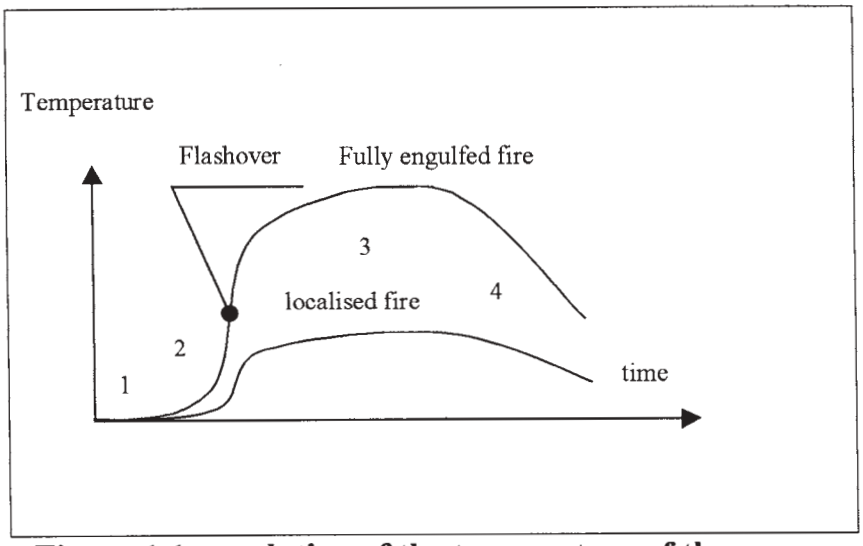


Figure 1.1 : evolution of the temperature of the gases

The ignition and the propagation phases of the fire depend mainly on the fuel characteristics because oxygen is widely available during these phases.

On the other hand, the amount of oxygen available has a big influence during the fully developed phase of the fire. Two situations are possible:

- There is enough oxygen to react with the material which is burning. The fire is said to be **fuel controlled** because the burning rate depends on the characteristics of the material.
- The openings of the compartment are too small, considering the size of the fire, and there is not enough oxygen to react with the all the available fuel. The fire is said **ventilation controlled** because the burning rate depends on the amount of available oxygen.

There are several possibilities to model the fire within a building. Some of the most widely used are described hereafter, in an increasing order of complexity.

1.2 NOMINAL FIRE CURVES

The simplest way to represent a fire is by a relation giving the evolution of the temperature of the gases as a function of time. Such functions are called *nominal fire curves*.

Historically, they were developed for the purpose of experimental testing of elements with the aim of classification of these elements, because it was highly desirable that different elements tested in different furnaces would be submitted to the same thermal action.

When it comes to representing a fire in a building, these curves are a very poor representation of reality. Yet, for historical reasons, because of the so many years during which they had been used, they continue to be, by far, the most often used representation of a fire in practical design applications. This is why the nominal fire curves are mentioned here, although they are far from any *natural fire safety concept.*

Some of the most widely used curves are represented on Figure 1.2, namely the hydrocarbon curve, the ISO curve, the ASTM curve and the external curve. It can be noticed that no cooling down phase is present in any of these curves. Another important feature is that there is only one temperature for the compartment, which means that the temperature is uniform in the compartment.

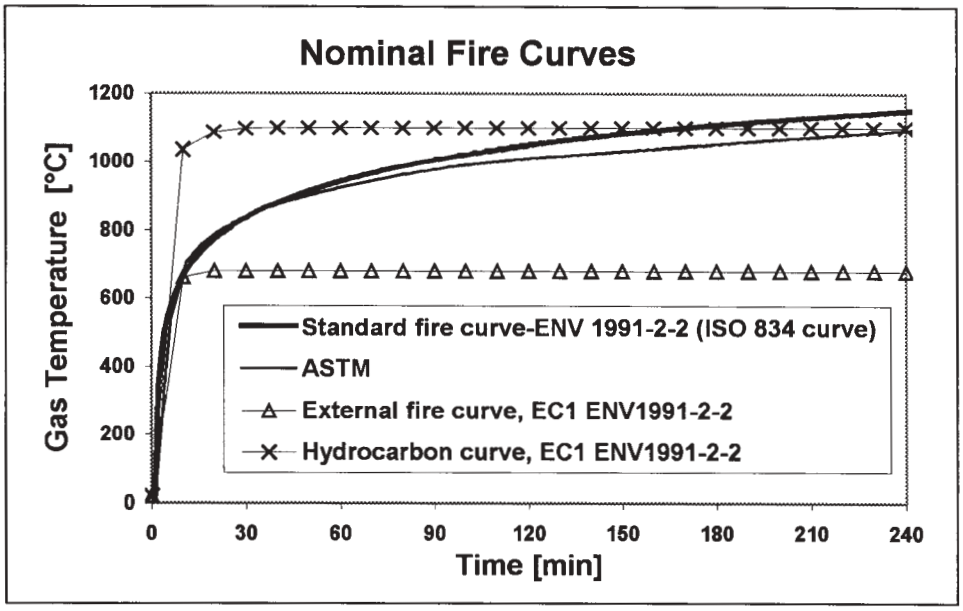


Figure 1.2 : nominal fire curves

There are only 2 ways by which some kind of fire safety design can be exercised using nominal fire curves:

1. By the choice of the nominal curve; usually the Hydrocarbon curve when any liquid fuel is supposed to burn, the external curve and the ISO or the ASTM curve for any fire in any building.
2. By the choice of the duration during which the fire has to be considered, 30, 60 or 90 minutes for example.

1.3 PARAMETRIC TEMPERATURE-TIME CURVE : ANNEX B OF ENV 1991-2-2

A parametric temperature-time curve is also a curve giving the evolution of the temperature of the gases as a function of time. The temperature is still uniform within the compartment but, on the contrary to the nominal curves, the relation depends on some physical parameters which have a significant influence on the severity of the fire that could develop in this compartment.

Historically, the first parametric curves were presented in Sweden by Petterson, based on the application of more sophisticated calculation tools and on comparison with experimental tests. Nowadays, the parametric curves presented in Annex B of Eurocode 1 are most often used.

In these parametric curves, the parameters having an influence on the curve are related to

- the fire load (the higher the fire load, the longer the fire),
- the geometry of the fire (bigger openings lead to shorter but more severe fires),
- the properties of the walls (walls absorbing energy limit the temperatures).

These 3 parameters are the data that the user has to supply for each particular case.

The parametric curves of Eurocode 1 are valid only within some limits of these parameters, namely;

- floor area ≤ 100 m² and floor to ceiling distance ≤ 4 m,
- no horizontal openings and a *reasonable* amount of vertical openings,
- concrete or brick type walls,
- a *reasonable* amount of combustible material (between 3 and 60 kg of wood / m²).

Figure 1.3 gives such a parametric curve obtained for a particular case. It can be observed that, once the 3 parameters have been identified, the curve gives the severity of the fire in terms of temperatures but also in terms of duration of the fire.

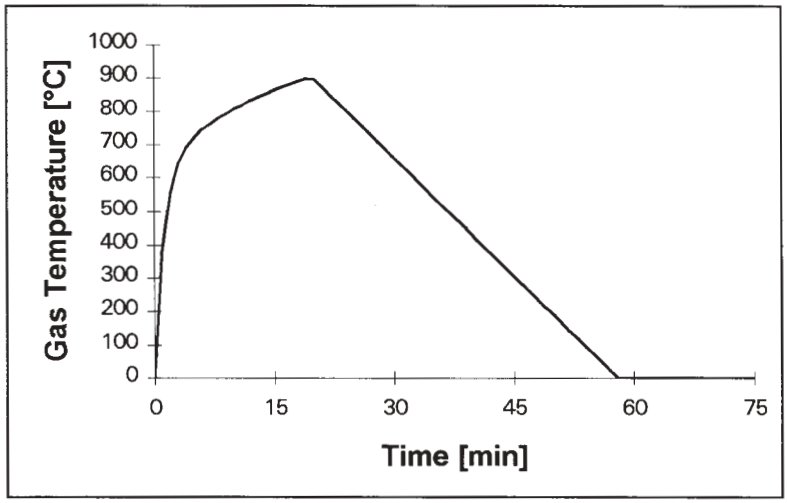


Figure 1.3 : a parametric temperature-time curve

1.4 ONE ZONE MODELS

One zone models is the name given to numerical programs which calculate the development of the temperature of the gases as a function of time, integrating the ordinary differential equations which express the conservation of mass and the conservation of energy in the compartment. These models are based on the fundamental hypothesis that the situation, i.e. the temperature, is uniform in the compartment.

The data have to be supplied with a higher degree of detail than for the parametric curves. For example,

- every dimension of the compartment and of the openings must be given here, instead of a single opening factor for a parametric curve,
- each wall can be described exactly with the presence of different materials if necessary, instead of one single thermal effusivity for a parametric curve,
- not only the quantity of combustible material has to be given, as it is the case for the parametric curves, but also the rate in time at which this energy is released.

Solving in detail the energy balance between the gas in the compartment, the walls, the openings and the energy released by the fire, and solving also the mass balance between the incoming and outgoing air through the openings as well as the combustion products released by the fire, one zone models give not only the evolution of the temperature of the gases in the compartment, but also additional information such as the temperatures in the walls or the velocity of the gases through the openings.

Figure 1.4 shows how a compartment is modelled, with different terms of the energy and mass balance represented.

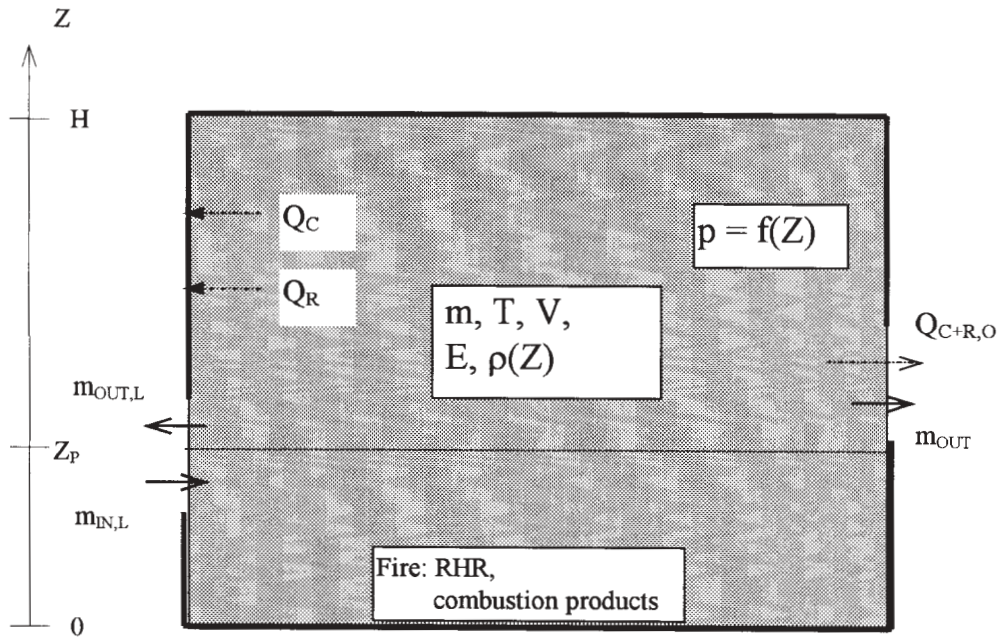


Figure 1.4 : a compartment in a one zone model

1.5 TWO ZONE MODELS

When the size of the fire is small compared to the size of the compartment in which its develops, the hypothesis of uniform temperature is not valid. Another hypothesis is based on the observation that in such a case there is an accumulation of combustion products in a layer beneath the ceiling (upper layer), with a more or less horizontal interface between this hot layer and the lower layer where the temperature of the gases remains much colder. The hypothesis of a two zone model is that the situation, i.e. the temperature, is uniform in each layer, but different from one layer to another.

The equations expressing the equilibrium of mass and of energy are written for each of the two layers and exchange between the two layers has to be considered.

The data to be supplied are the same as those supplied for one zone models. They concern the description of the geometry of the compartment, the definition of the walls, the openings and the combustible material.

As a result of the simulation, a gas temperature is given in each of the two layers, as well as information on wall temperatures and flux through the openings. An important result is the evolution as a function of time of the thickness of each layer. The thickness of the lower layer, which remains at rather cold temperature and contains no combustion product, is very important to judge the tenability of the compartment for the occupants.

It has to be judged by the user whether the results are still consistent with the hypothesis of the two zone stratification. This is for example not the case if the thickness of the upper layer increases so much that it actually fills the whole compartment. Another case is when the temperature in the upper layer is so high that it leads to the flash-over in the whole compartment, destroying the layer stratification and producing a situation which is closer to the hypothesis of a one zone model. In any of these two cases, it is necessary to continue the simulation under the hypothesis of a one zone model.

Figure 1.5 shows how a compartment is modelled by a two zone model, with different terms of the energy and mass balance represented.

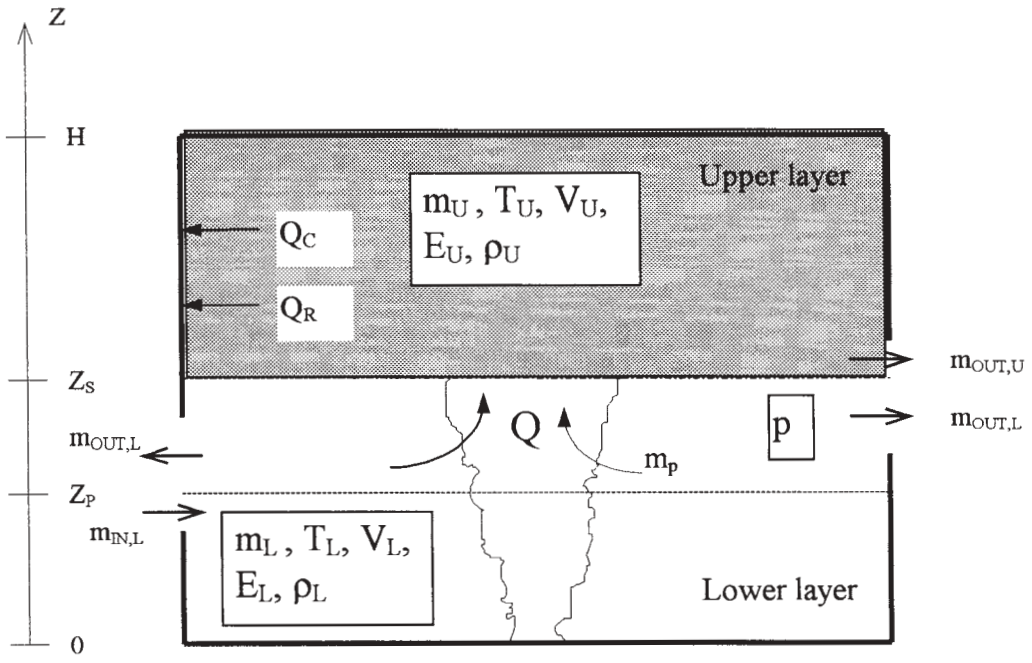


Figure 1.5 : a compartment in a two zone model

Figure 1.5 is typical of a simple situation where the compartment exchanges mass and energy only with the outside environment. These kinds of models have yet the capability to analyse more complex buildings where the compartment of origin exchanges mass and energy with the outside environment but also with other compartments in the building. This is of particular interest to analyse the propagation of smoke from the compartment of origin towards other adjacent compartments where it can also be a thread for life. Such a situation, analysed by *multi-compartment two zone models*, is depicted on Figure 1.6.

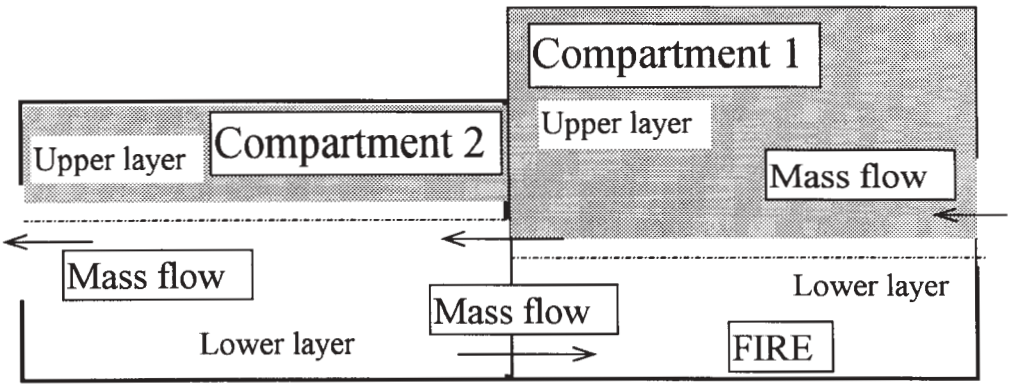


Figure 1.6 : a compartment in a multi-compartment two zone model

1.6 COMPUTATIONAL FIELD MODEL

In field models, the partial differential equations of the thermodynamic and aerodynamic variables are solved in a very large number of points in the compartment. These equations are usually solved by finite volume method.

Two types of field models exists :

1. Direct Numerical Simulations (DNS): the basic equations are solved in their whole complexity. Such codes need very short time steps and very refined spatial grids in order to simulate all time and spatial scales coming from the turbulent and the chemical scales. DNS needs extremely long computational time and are used only for academic cases or very simple applications.
2. Computation Fluid Dynamic (CFD): the basic equations are pre-averaged on the time scale, which makes high frequency vibrations disappear, and a turbulent model takes into account the short spatial scales.

The data to be input are basically the same as in the zone models, which means that the rate of combustion has also to be given as an input.
The results are given with a much greater degree of details because the variables, such as temperature, velocity and chemical species concentration, are given in all the points of the grid defining the compartment.

Figure 1.7 illustrates how a compartment is modelled by a field model, although any real application would require a much finer grid.

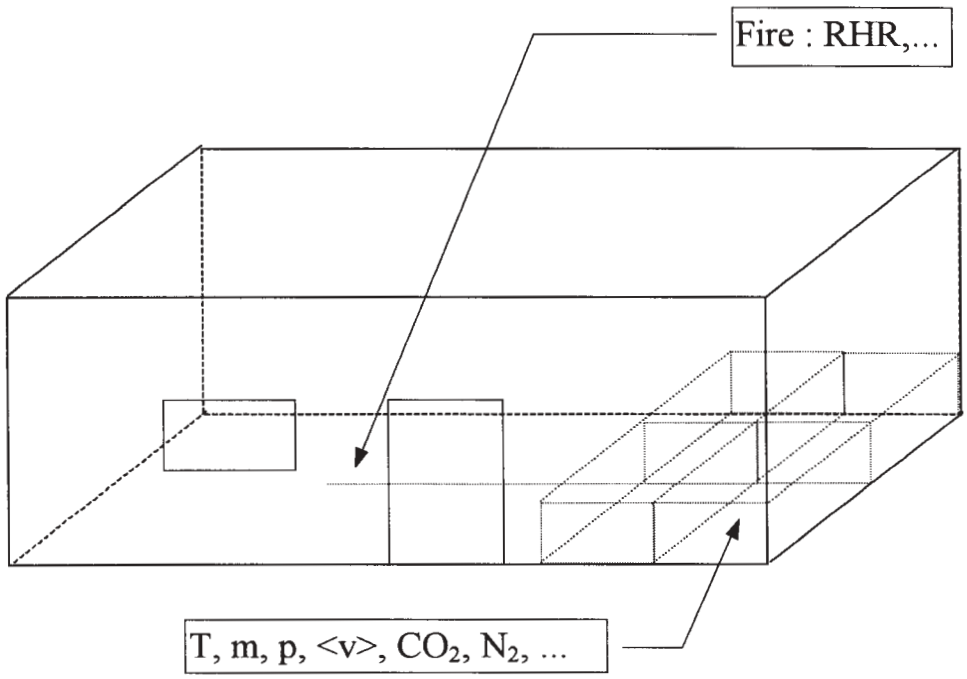


Figure 1.7 : a compartment in a field model

The turbulent model can be a second order closed or $k-\varepsilon$ model. At the time being, the $k-\varepsilon$ model is often used. It must be noticed that most of the flows induced by fire do not have characteristics of fully turbulent flow. So the use of $k-\varepsilon$ model (standard or modified versions) is often controversial.

1.7 CONCLUSIONS

Because of the complexity and the long CPU time, there are few applications of field models in simulation of fire resistance, especially in case of fully developed fire. In fire domain, the use of field models is reduced to the application to smoke movement. In such codes, combustion models have never been used in building fire simulation, and the fire is modelled as an energy source term (without mass rate). Furthermore, field models use different parameters obtained from experiments (such as rate of heat release), and so far field models have been applied to simple geometries only (mainly a single compartment).

These comments show that the development of zone models (especially the development of additional model such as air entrainment or combustion models) is not yet stopped, and their applications will be numerous during several years.

2 ONE ZONE MODELS

The main assumption of one zone models is that the temperature in the compartment is uniform. One zone models are then only valid in post-flashover conditions, it means a fully developed fire or when the hot layer of a localised fire is thick and fill all the compartment. Homogeneous properties of the gas inside the compartment are assumed.

Exchanges of mass between, on one hand, the inside of the compartment and, on the other hand, the external world (through openings) and the fire (pyrolisis rate) are considered.

Exchanges of energy between, on one hand, the inside of the compartment and, on the other hand, the external world (through openings), the fire (rate of heat release) and the walls are considered.

The low computing time and the realist hypothesis of uniform temperature in case of fully developed fire make the one zone model a helpful tool to estimate the temperature in a compartment in post-flashover condition.

2.1 FUNDAMENTALS

2.1.1 BASIC EQUATIONS

The six physical variables which are considered to describe the gas in the compartment are usually :

- T, the temperature of the gas;
- m, the mass of the gas inside the compartment;
- V, the volume of the compartment;
- E, the internal energy inside the compartment;
- ρ, the gas density;
- p, the pressure in the compartment.

In some codes, other physical variable (such as oxygen concentration, optical properties,...) can be considered.

The four constraint equations are:

$$\rho = \frac{m}{V}$$

$$E = c_v m T$$

$$p = \rho R T$$

$$V = cst$$

The basic assumption is that the physical properties of the gas (T, m, E, ρ, p) are uniform (or uniformly distributed) on the whole compartment. The volume of the compartment is constant.

The mass balance and the energy balance on the whole compartment are :

$$\frac{\partial m}{\partial t} = \frac{\partial m_{in}}{\partial t} - \frac{\partial m_{out}}{\partial t}$$
$$\frac{\partial E}{\partial t} = \frac{\partial E_{in}}{\partial t} - \frac{\partial E_{out}}{\partial t}$$

With m_{in} (E_{in}), the mass (energy) added to the compartment and m_{out} (E_{out}), the mass (energy) lost by the compartment

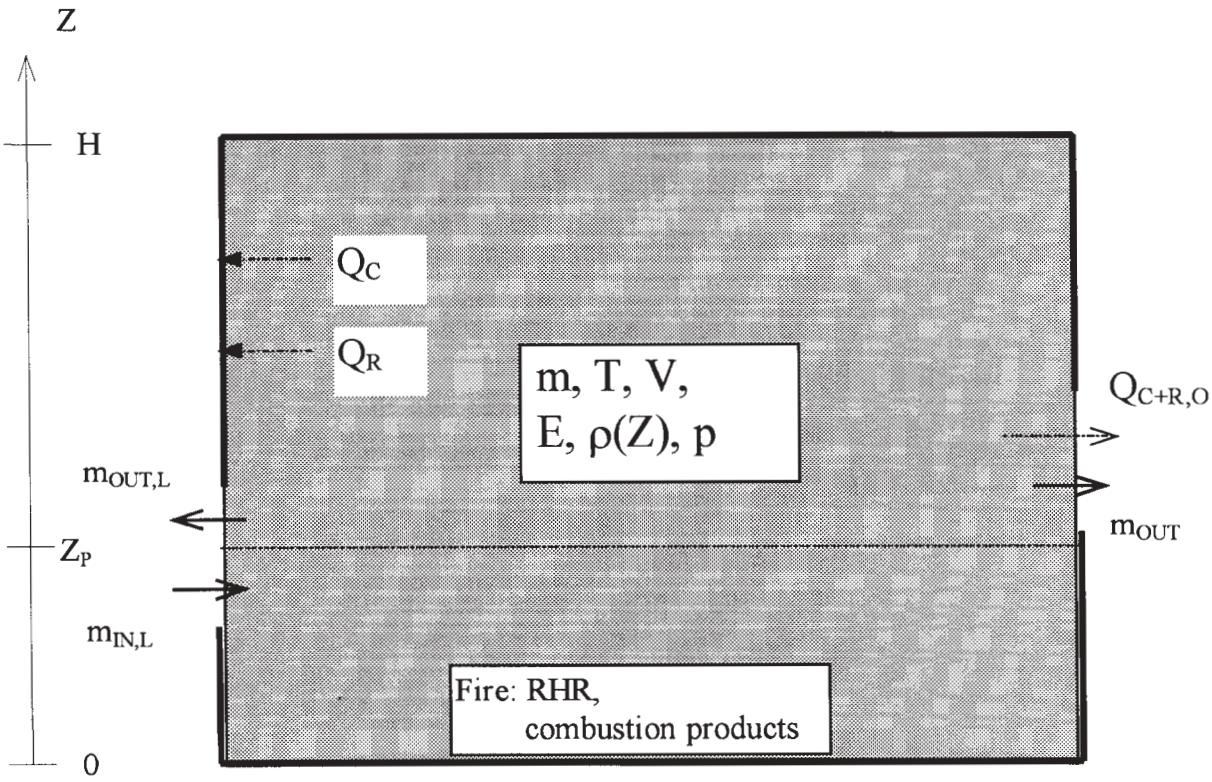


Figure 2.1

The temperature and the mass of the gas in the compartment are calculated step by step in function of time by solving the energy balance and the mass balance equations.

2.1.2 SUB-MODELS

a. Energy released by the fire

In one zone models, the most simple way to model the energy released by the fire is to define a rate of heat release curve (RHR) giving the power released by the fire as a function of time. The pyrolisis rate (mass of combustion products released by the fire) can also be defined.
More sophisticated combustion models can be developed to take into account for instance the ventilation conditions or other combustion phenomena.

b. Gas exchanges through openings

Even if in the basic equation the pressure is assumed to be constant, in order to calculate the mass exchanges with the external world the variation of pressure with the altitude has to be calculated and can be considered as linear or exponential.

The mass exchange through openings is usually calculated by integrating the Bernoulli formula or by using a more complex model of fluid dynamics.
The Bernoulli formula is written:

$$\Delta p = \frac{1}{2}\rho v^2$$

$$\dot{m} = Kb\int_{z'}^{z''} \frac{P_A(z)}{RT_A}\sqrt{2RT_A\left(1-\frac{P_B(z)}{P_A(z)}\right)}dz$$

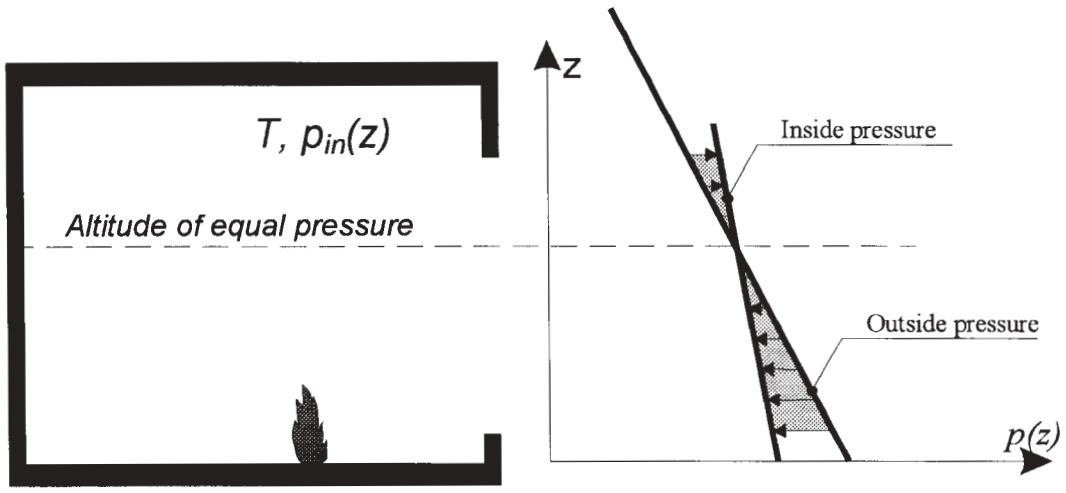


Figure 2.2

c. *Wall model*

The simplest way to estimate the energy loss to and through the partitions is to set it to a fraction of the RHR. During this research it has been shown that this method is not acceptable because this term is often the biggest one in the energy balance.
The numerical model which is commonly used is the 1D finite differences. In ozone a finite element model is used (see Chapter 6).

2.2 EXISTING PROGRAMS

In the world, different one zone models exist as CISNV from Russia, NAT from France, Petterson from Sweden, COMPF from USA ... The first codes were developed in 1977. The basis of the models is always the same: homogeneity of the properties of internal gases, often named a well-stirred reactor assumption.
Around this assumption, two balance equations (energy and mass) have to be solved. The terms of the equations could be more or less simplified. The cases of the models Nat and Petterson are given to show the example of simplifications sometimes made.

Petterson :

The Petterson model developed by Magnusson and Thelandersson [YY1] in 1970 was a precursor of simulation fires in enclosures. Nevertheless, as a precursor, the Petterson model needed some simple assumptions. The model is based only on the heat balance equation. The unsteady state is assumed to be a succession of quasi-steady state : it means that the Internal energy balance is zero. The equation is given by a balance between the heat release by the fire (I_c) and the energy lost through window by radiation (I_r) and by mass exchange (I_L) and to the walls :

$$I_c = I_L + I_r + I_W$$

The energy loss through walls is determined by resolution of one-dimension heat conduction in walls. The rate of heat release and the mass exchange by openings are assessed considering the relation of kawagoe. Knowing every terms of the equation given herein above, the temperature is deduced by the implicit resolution of this equation.

This model does not solve the fundamental equations but solves a simplified energy balance.

NAT:

This model was developed at CSTB in France by Michel Curtat [YY2]. The first works were made at the beginning of the 80's. The model solves the fundamental energy and mass balances equations in the compartment with a commercial library.

The heat conduction through walls is solved in an explicit finite difference scheme. It can take into account the variation with temperature of wall characteristics, the radiative exchanges between walls and between walls and gases. The modification in time of opening can be used, considering the characteristics of the barriers. NAT is used as a fire engineering tool, nevertheless is not a commercialised product.

References :

[YY1] Magnusson S.E. and Thelandersson S.
'Temperature-time curves of complex process of fire development' - Acta Polytechnica scandinavia - Stockholm 1970.

[YY2] Michel Curtat
'Modèle et code de calcul de feu développé dans une pièce unique' - CSTB - Octobre 1981

2.3 INPUT DATA

The data which have to be provided to one zone models are:

- geometrical data: dimensions of the compartment, of the openings and of the partitions;
- material properties of walls;
- fire data: RHR, pyrolisis rate, combustion heat of fuel.

2.4 APPLICATION RANGE

One zone models are valid in post-flashover conditions, it means in fully developed fire or when the hot layer of a localised fire is thick and fill all the compartment. (See chapter 8 for a complete description of the application rage of zone models).

2.5 MOTIVATIONS FOR A NEW ONE ZONE MODEL

The Working Group 1 of the research "Natural Fire Safety Concept" has decided to make a new one zone model called OZone. This code is presented in chapter 6 of this report. The main reasons which lead the group to do it are:

- *The ownership of the code*: the members of the Working Group 1 have different zone models but they do not possess the source files and they do not have the right to modify the existing codes.
- *The knowledge and the understanding.*
- *Some numerical properties*: Stability - Robustness - CPU time. The last developments made on numerical properties of zone model have been used.
- *Implicit wall model*: all existing codes have an explicit wall model, OZone has an implicit wall model.
- *Easy improvements*: i.e. a combustion model has been developed and included in OZone.

3 TWO ZONE MODELS

3.1 FUNDAMENTALS

A two zone model is based on the basic assumption that a fire compartment can be divided into two regions or zones, an upper hot gas layer and a lower cold gas layer, each with approximately uniform conditions. There are mass and energy exchanges between these zones, with the fire and with the external world.

The application of this model is mainly in pre-flashover conditions and for localised fires (see chapter 8). Besides calculating the evolution of gas temperature, these models are used in order to estimate the life safety in function of smoke layer height, toxic gas concentration, radiative flux and optical density.

A multi-compartments two zone model allows to follow the smoke propagation through different rooms.

As in all zone fire models, the conservation laws are applied for each zone or control volume: the conservation of mass or continuity equation, the conservation of energy or the first law of thermodynamics, the ideal gas law and definitions of density and internal energy. The conservation of momentum is ignored.

Many differential equation formulations based upon these assumptions can be derived and different two zone fire models have been developed. These different formulations are mathematically equivalent but not necessarily numerically equivalent (stiff problem).

Each differential formulation can be expressed in terms of mass and energy flow rates. These flow rates represent the exchange of mass and/or energy between the two zones due to physical phenomena or sub-models such as fire plumes, natural and forced vents, convective and radiative heat transfer, etc. For example a vent exchanges mass and energy between zones in connected rooms, a fire plume typically adds heat to the upper layer and transfers entrained mass and energy from the lower to the upper layer and convection transfers energy from the gas layers to the surrounding walls.

3.1.1 THEORETICAL BASIC FORMULATIONS OF TWO ZONE MODEL

A two zone model is typically based on the following assumptions:

- the mass flow rate to the upper and lower layers, denoted $\dot{m}_u$ and $\dot{m}_l$, and the energy flow rate to the upper and lower layers, denoted $\dot{q}_u$ and $\dot{q}_l$, may be computed in terms of zone properties such us temperatures, densities, etc;

- the gas in each layer is defined by his mass, internal energy, density, temperature and volume denoted respectively by m_i, E_i, ρ_i, T_i and V_i where i=L for the lower layer and i=U for the upper layer; (10 variables).
- the compartment as a whole has a uniform pressure P (note that this assumption is not considered when calculating mass exchanges), (1 variables).

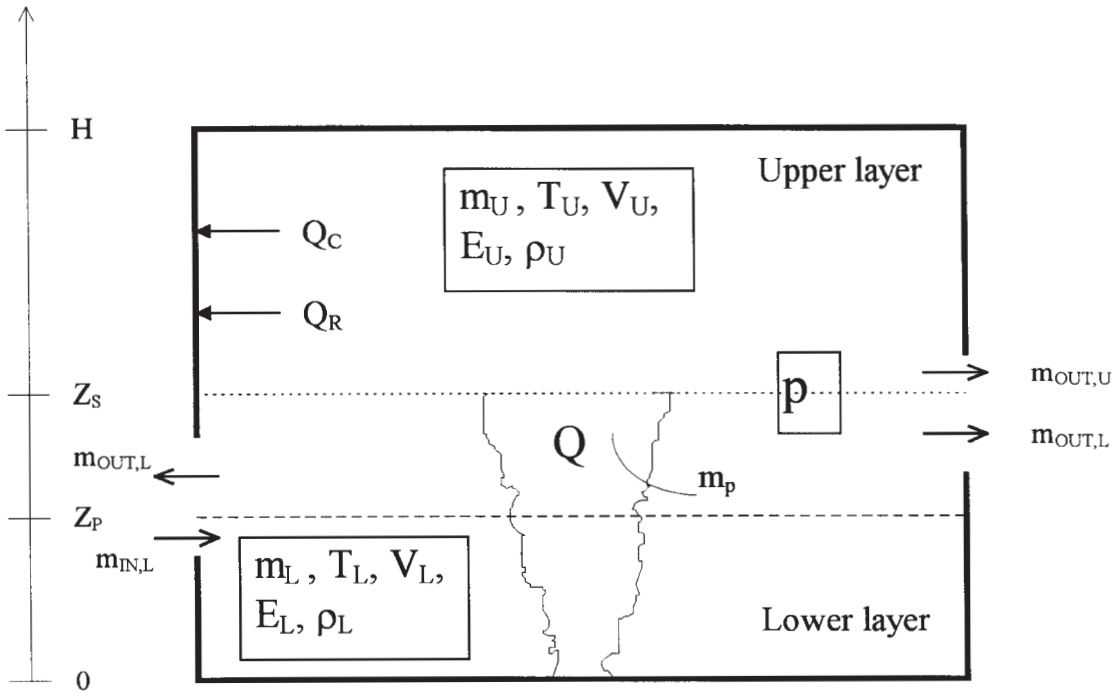


Figure 3.1: two zone model

The eleven variables are related by means of the following seven constraints:

$\rho_i = m_i / V_i$ i = U, L.

$E_i = c_v m_i T_i$

$p = R \rho_i T_i$

$V = V_U + V_L$

Differential equations for each of the eleven variables are derived from the mass balance and the energy balance:

Masse: $$\frac{dm_i}{dt} = \dot{m}_i$$

Pressure: $$\frac{dP}{dt} = \frac{\gamma - 1}{V}(\dot{q}_L + \dot{q}_U)$$

Energy: $$\frac{dE_i}{dt} = \frac{1}{\gamma}(\dot{q}_i + V_i \frac{dP}{dt})$$

Volume: $$\frac{dV_i}{dt} = \frac{1}{\gamma P}\left[(\gamma - 1)\dot{q}_i - V_i \frac{dP}{dt}\right]$$

Density: $$\frac{d\rho_i}{dt} = \frac{-1}{c_p T_i V_i}\left[\left(\dot{q}_i - c_p \dot{m}_i T_i\right) - \frac{V_i}{(\gamma - 1)}\frac{dP}{dt}\right]$$

Temperature: $$\frac{dT_i}{dt} = \frac{1}{c_p \rho_i V_i}\left[\left(\dot{q}_i - c_p \dot{m}_i T_i\right) + V_i \frac{dP}{dt}\right]$$

where: $$\gamma = \frac{c_p}{c_v}$$

We have then a set of eleven equations which have to be solved to find the value of the eleven variables at each time during the fire.

3.1.2 SUB-MODELS

a. Energy released by the fire

The energy of the source is defined by the rate of heat released during the fire (an example is given on Figure 3.3) or by the pyrolisis rate.
The radiation of the flame to the external world is generally taken into account by multiplying the RHR by factor (0,65 is a value often used).

b. Entrained air

The mass entrained from the lower layer to the upper layer can be taken into account by different models. These models are very important because they have a direct influence on the thickness of the upper layer. We can quote some of them:

- ZUKOSKI model:

$$\dot{m}_p = 0{,}21\left(Q^*\right)^{1/3}\rho_1(0)Z_s^2\sqrt{gZ_s}$$

where $$Q^* = \frac{(1-\lambda_r)\dot{Q}}{\rho_1(0)Z_s^2\sqrt{gZ_s}\,T_1 Cp(T_1)}$$

- MITLER model:

$$\dot{m}_p = 0{,}106\left(Q^*\right)^{1/3}\rho_1(0)Z_s^2\sqrt{gZ_s}$$

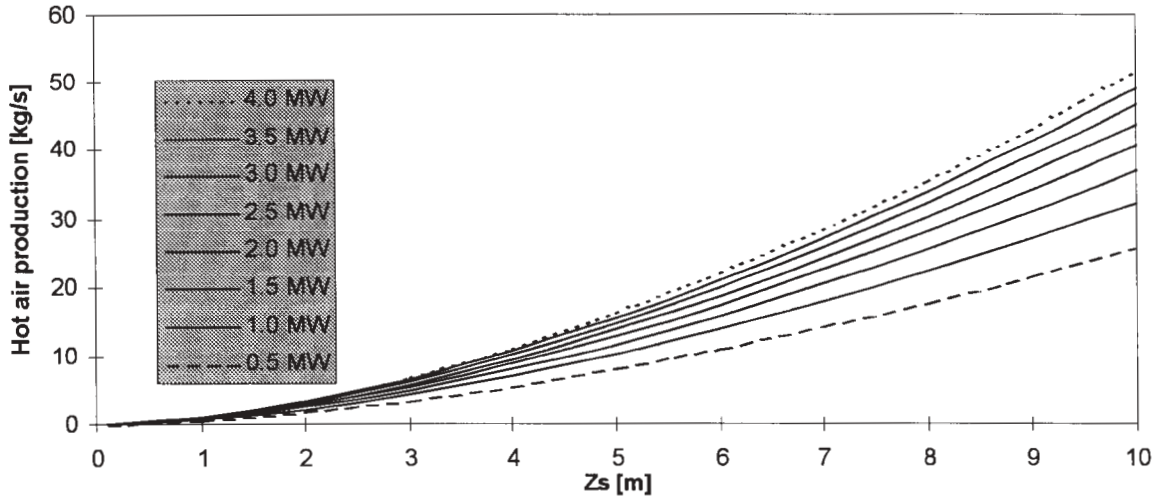


Figure 3.2: Zukoski model

Zukoski model gives for the mass of entrained air two times the value given by the Mitler model.

- MITLER model:

The variation of the mass flow rate, m in [kg/s], with the rate of convective heat release, q_c in [kW], and the height above the source of heat, z in [m], is calculated from the following equations:

- *Continuous flame:*

$$\frac{m}{q_c}=0{,}011\left(\frac{z}{q_c^{0,4}}\right)^{0,566} \quad \text{for} \quad 0<\frac{z}{q_c^{0,4}}<0{,}08$$

- *Intermittent:*

$$\frac{m}{q_c}=0{,}026\left(\frac{z}{q_c^{0,4}}\right)^{0,909} \quad \text{for} \quad 0{,}08<\frac{z}{q_c^{0,4}}<0{,}2$$

- *Plume:*

$$\frac{m}{q_c}=0{,}124\left(\frac{z}{q_c^{0,4}}\right)^{1,895} \quad \text{for} \quad 0{,}2<\frac{z}{q_c^{0,4}}$$

The model takes also into account the constraint on the quantity of gas which can be entrained by a plume arising from fire. This constraint is:

$$\dot{m}_e<\frac{\dot{Q}}{c_p(T_U-T_L)}$$

c Pressure

The variation of pressure with the altitude can be linear or exponential when considering the exchange of mass between zones and the outside of the compartment.

d Masse flow through vents

The mass flow through vents is calculated by integrating the Bernoulli's law on each opening.

$$\Delta p = \frac{1}{2}\rho v^2$$

$$\dot{m} = Kb\int_{Z'}^{Z''} \frac{P_A(z)}{RT_A}\sqrt{2RT_A\left(1-\frac{P_B(z)}{P_A(z)}\right)}dz$$

If the altitude of equal pressure (Z_P) between the inside and the outside of the compartment is in an opening, the openings is divided in two parts, one where the mass flow goes inside the compartment and the other one where the mass flow goes outside. If the separation of the zones (Z_S) is in an opening, a subdivision of the vent is also made.

In some code a back mixing is encountered.

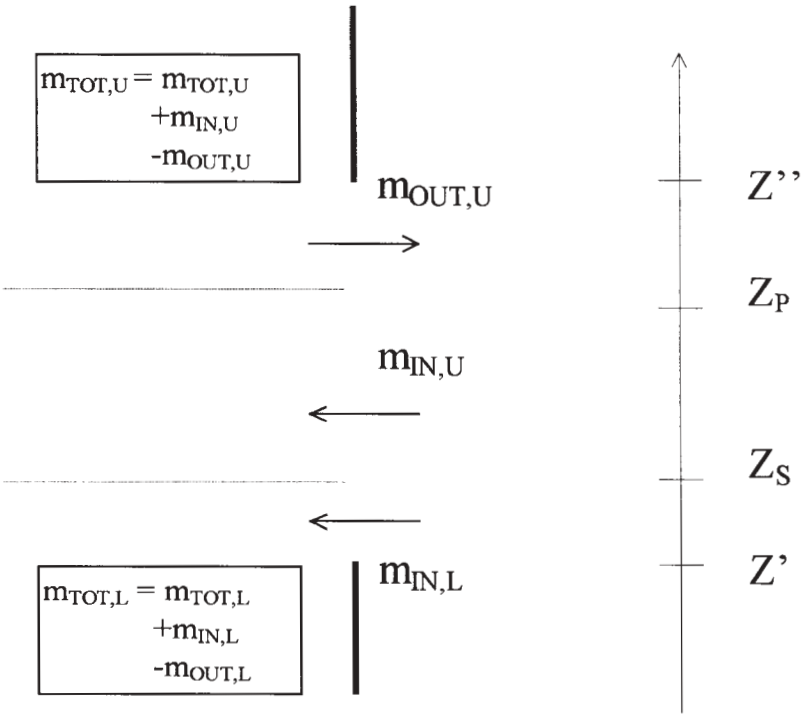


Figure 3.3

e Wall model

The energy loss to the walls is calculated with the following expression:

$$\dot{Q}_{wall} = \dot{Q}_{conv} + \dot{Q}_{rad}$$

where

$\dot{Q}_{conv}$ is the term of convection,

$\dot{Q}_{rad}$ is the term of radiation.

$$\dot{Q}_{conv} = h(T_U - T_S)A_S$$

$$\dot{Q}_{rad} = \varepsilon\sigma(T_U{}^4 - T_S{}^4)A_S$$

where $A_s = A_{wall} - A_{openings}$

T_s: the temperature of the skin of the wall

The heat transferred through the wall is obtained using the expression of the conduction:

$$\lambda \frac{\partial^2 T}{\partial x^2} = c\rho \frac{\partial T}{\partial t}$$

The wall is divided in some layers and the equations are generally solved by finite differences.

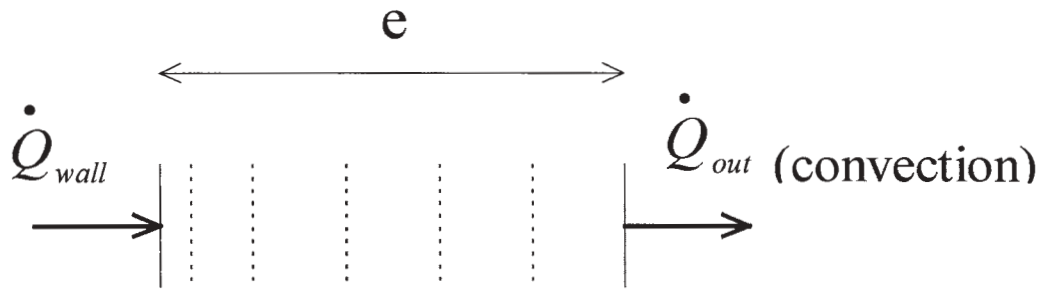


Figure 3.4

3.2 EXISTING TWO ZONE MODELS

A lot of two zone models have been developed. For example:

- CTT, developed at University of Liege
- FIRST, CCFM and CFAST, developed at NIST, USA
- ARGOS, developed at Danish Institute of Fire Technology, Denmark
- …

4 COMPUTATIONAL FIELD MODELS (CFD)

4.1 FUNDAMENTALS

Computational Fluid Dynamics, or CFD, analyses systems involving fluid flow, heat transfer and associated phenomena by solving the fundamental equation of the fluid flow. These equations represent mathematical statement of the conservation laws of physics.

- The mass of a fluid is conserved.
- The rate of change of momentum equals the sum of the forces on a fluid particle (Newton's second law)
- The rate of change of energy is equal to the sum of the rate of heat addition to and the rate of work done on a fluid particle (first law of thermodynamics).

Additional equations are solved for the conservation of the parameters of the k-e turbulence model, chemical species.

CFD codes are structured around the numerical algorithms to solve the fundamental equation. Codes contain three main elements: **(a)** a pre-processor, **(b)** a solver and **(c)** a post-processor. We briefly examine the function of each of these elements within the context of a CFD code.

(a) Pre-processor

Pre-processing consists of the input of a flow problem. The user activities at the pre-processing stage involve:

- Definition of the geometry of the region of interest: the computational domain.
- Grid generation: the sub-division of the domain into a number of smaller, non-overlapping sub-domains: a grid (or mesh) of cells (or control volumes or elements).
- Selection of the physical and chemical phenomena that need to be modelled.
- Definition of fluid properties.
- Specification of appropriate boundary conditions at cells which coincide with or touch the domain boundary.

The solution to a flow problem (velocity, pressure, temperature etc.) is defined at nodes inside each cell. The accuracy of a CFD solution is governed by the number of cells in the grid. In general, the larger the number of cells the better the solution accuracy. Both the accuracy of a solution and its cost in terms of necessary computer hardware and calculation time are dependent on the fineness of the grid. Optimal meshes are often non-uniform: finer in areas where large variations occur from point to point and coarser in regions with relatively little change. Efforts are under way to develop CFD codes with a (self-) adaptive meshing capability. At present it is still up to the skills of the CFD user to design a grid that is a suitable compromise between desired accuracy and solution cost.

(b) Solver

There are three distinct streams of numerical solution techniques: finite difference, finite element and spectral methods. In outline the numerical methods that form the basis of the solver perform the following steps:

- Approximation of the unknown flow variables by means of simple functions.
- Discretisation by substitution of the approximations into the governing flow equations and subsequent mathematical manipulations.
- Solution of the algebraic equations.

The main differences between the three separate streams are associated with the way in which the flow variables are approximated and with the discretisation processes.

Finite Difference Methods. Finite difference methods describe the unknowns ϕ of the flow problem by means of point samples at the node points of a grid of co-ordinate lines. Truncated Taylor series expansions are often used to generate finite difference approximations of derivatives of ϕ in terms of point samples of ϕ at each grid point and its immediate neighbours. Those derivatives appearing in the governing equations are replaced by finite differences yielding an algebraic equation for the values of ϕ at each grid point.

Finite Element Method. Finite element methods use simple piecewise functions (e.g. linear or quadratic) valid on elements to describe the local variations of unknown flow variables ϕ. The governing equation is precisely satisfied by the exact solution ϕ. If the piecewise approximating functions for ϕ are substituted into the equation it will not hold exactly and a residual is defined to measure the errors. Next the residuals (and hence the errors) are minimised in some sense by multiplying them by a set of weighting functions and integrating. As a result we obtain a set of algebraic equations for the unknown coefficients of the approximating functions. The theory of finite elements has been developed initially for structural stress analysis.

Spectral Methods. Spectral methods approximate the unknowns by means of truncated Fourier series or series of Chebyshev polynomials. Unlike the finite difference or finite element approach the approximations are not local but valid throughout the entire computational domain. Again we replace the unknowns in the governing equation by the truncated series. The constraint that leads to the algebraic equations for the coefficients of the Fourier or Chebyshev series is provided by a weighted residuals concept similar to the finite element method or by making the approximate function coincide with the exact solution at a number of grid points.

The finite volume method. The finite volume method was originally developed as a special finite difference formulation. The numerical algorithm consists of the following steps:

- Formal integration of the governing equations of fluid flow over all the (finite) control volumes of the solution domain.
- Discretisation involves the substitution of a variety of finite-difference-type approximations for the terms in the integrated equation representing flow processes such as convection, diffusion and sources. This converts the integral equations into a system of algebraic equations.
- Solution of the algebraic equations by an iterative method.

The first step, the control volume integration, distinguishes the finite volume method from all other CFD techniques. The resulting statements express the (exact) conservation of relevant properties for each finite size cell. This clear relationship between the numerical algorithm and the underlying physical conservation principle forms one of the main attractions of the finite volume method and makes its concepts much more simple to understand by engineers than finite element and spectral methods. The conservation of a general flow variable ϕ, for example a velocity component or enthalpy, within a finite control volume can be expressed as a balance between the various processes tending to increase or decrease it. In words we have:

Rate of change of ϕ in the control volume with respect to time =
Net flux of ϕ due to convection into the control volume +
Net flux of ϕ due to diffusion into the control volume +
Net rate of creation of ϕ inside the control volume

CFD codes contain discretisation techniques suitable for the treatment of the key transport phenomena, convection (transport due to fluid flow) and diffusion (transport due to variations of ϕ from point to point) as well as for the source terms (associated with the creation or destruction of ϕ) and the rate of change with respect to time. The underlying physical phenomena are complex and non-linear so an iterative solution approach is required. The most popular solution procedures are the TDMA line-by-line solver of the algebraic equations and the SIMPLE algorithm to ensure correct linkage between pressure and velocity. Commercial codes may also give the user a selection of further, more recent, techniques such as Stone's algorithm and conjugate gradient methods.

(c) Post-processor

As in pre-processing a huge amount of development work has recently taken place in the post-processing field. Owing to the increased popularity of engineering workstations, many of which have outstanding graphics capabilities, the leading CFD packages are now equipped with versatile data visualisation tools. These include:

- Domain geometry and grid display
- Vector plots
- Line and shaded contour plots
- 2D and 3D surface plots
- Particle tracking
- View manipulation (translation, rotation, scaling etc.)
- Colour postscript output

More recently these facilities may also include animation for dynamic result display and in addition to graphics all codes produce trusty alphanumeric output and have data export facilities for further manipulation external to the code.

A good understanding of the numerical solution algorithm is crucial. Three mathematical concepts are useful in determining the success or otherwise of such algorithms: convergence, consistency and stability. Convergence is the property of a numerical method to produce a solution which approaches the exact solution as the grid spacing, control volume size or element size is reduced to zero. Consistent numerical schemes produce systems of algebraic equations which can be demonstrated to be equivalent to the original governing equation as the grid spacing tends to zero. Stability is associated with damping of errors as the numerical method proceeds. If a technique is not stable even round off errors in the initial data can cause wild oscillations or divergence.

4.2 INPUT DATA

As a first step in the analysis process, application of CFD to the natural fire modelling requires the definition of different characteristics : geometry of the fire scenario, space discretization (grid generation), selection of the equation to be solved (radiation, ...), materials properties (Fluid : air. Solids : walls, beams, columns, ...), flow conditions in the limits of the model (boundary conditions) and sources in the model (heat sources, fans, ...).

Geometry. Nowadays, geometry models are widely extended due to the common use of the CAD tools in a lot of fields related with engineering. In the case of the application to the natural fire modelling, these step consists on the representation of the physical dimensions of the fire scenario including walls, beams, columns and any object that limits or is included in the domain of interest.

Space discretization. Once the geometry is defined it has to be subdivided into a number of finite number of control volumes, or cells, where the partial differential equation will be discretized by the solver. The resulting set of cells are known as 'grid of the model'.

Description of the phenomena. As CFD codes has a wide range of application, they can solve different governing sets of equation depending of the studied phenomena. The transient flow of the air in a fire scenario has the following characteristics that have to be taken into account in the equation describing the phenomena :

- time dependence behaviour
- turbulent flow (buoyancy effect on turbulence)
- thermal calculation (conduction, convection and radiation)

Materials properties. The physical properties of the materials involved in the scenario have to be set. The physical properties define the behaviour of the fluid (air) as well as the solids (concrete walls, steel beams, etc.). These properties are : density, viscosity, thermal conductivity and specific heat.

Boundary conditions. Due to the discrete formulation of the equations it is necessary to define the distribution of the variables in the external limits of the domain. In fire scenario modelling, three conditions are usually applied :

- Pressure boundary condition : It sets the static pressure of the flow at this location.
- External convection heat flux : determines the value of the external temperature and the value of the convection coefficient from walls to external environment.
- Velocity boundary condition : It sets the velocity of the air flow through windows in case it is known (forced ventilation scenarios).

Sources. In addition to the equations describing the general behaviour of the fluids and solids, particular sources terms can be added. These terms are used to introduce the rate of heat release in the location of fire and other aspects in the fluid flow as fans or special pressure dropping through openings.

4.3 APPLICATION RANGE

The first limitation in the application of CFD to the modelization of fire scenarios and natural fire behaviour is the computational cost. CFD capabilities allow to perform two or three dimensional models taking into account a lot of different cases but its accuracy is hardly related with the size of the cells of the greed. So, while a large number of cells is desired in order to get most of the details in the model, solving a big set of descretized equations containing particular terms (radiation) makes computer hardware and calculation time requirements prohibitive. The model size, and hence, the grid design have to be a compromise between desired accuracy and solution cost.
It has also to be realised that the final results depend on the main input, i.e. on the rate of heat release curve chosen by the user.

At present, CFD capabilities embrace :
- steady and unsteady single phase flows
- laminar or turbulent flows
- thermal calculation including heat conduction within solid boundaries
- fluids laden with a disperse phase of reacting or non-reacting particles or droplets
- fluids containing multiple reacting chemical species including surface reaction
- combustion
- radiant heat transfer
- gravity/buoyancy

4.4 EXAMPLES

As examples of application of the CFD to the natural fire field we can present the following two cases:

1. Air entrainment into buoyant plume.

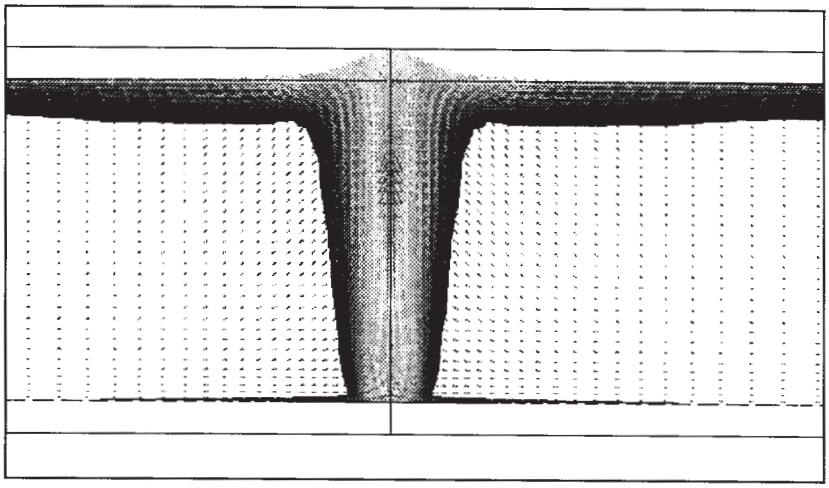


Figure 4.1 Buoyant plume modelization

2. Natural convection and temperature evolution of air in a large compartment (closed car park) heated by the RHR of the combustion of a car.

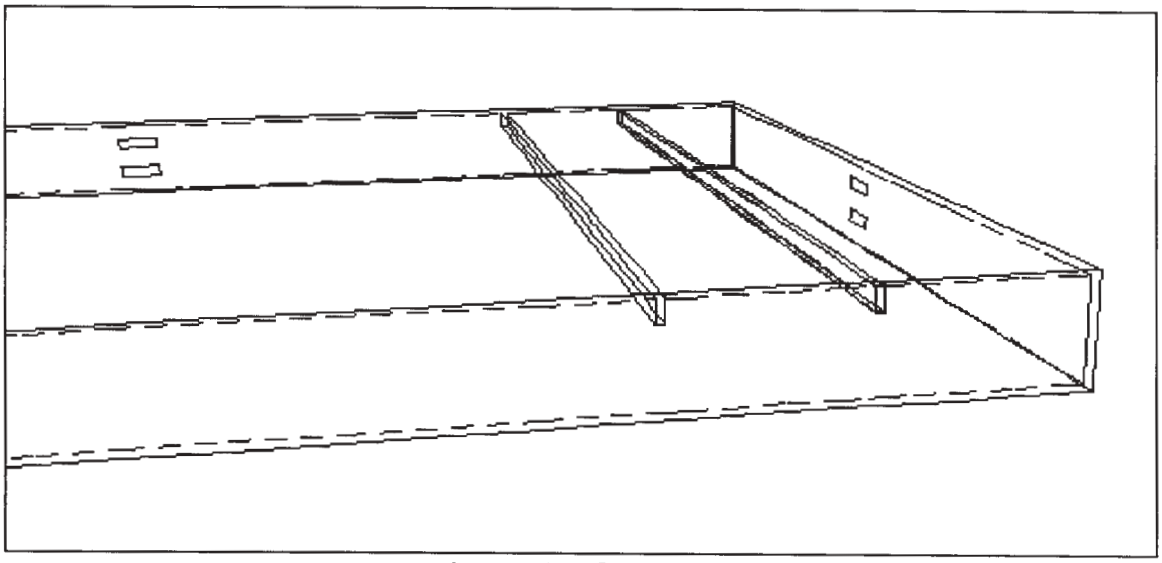


Figure 4.2 Geometry

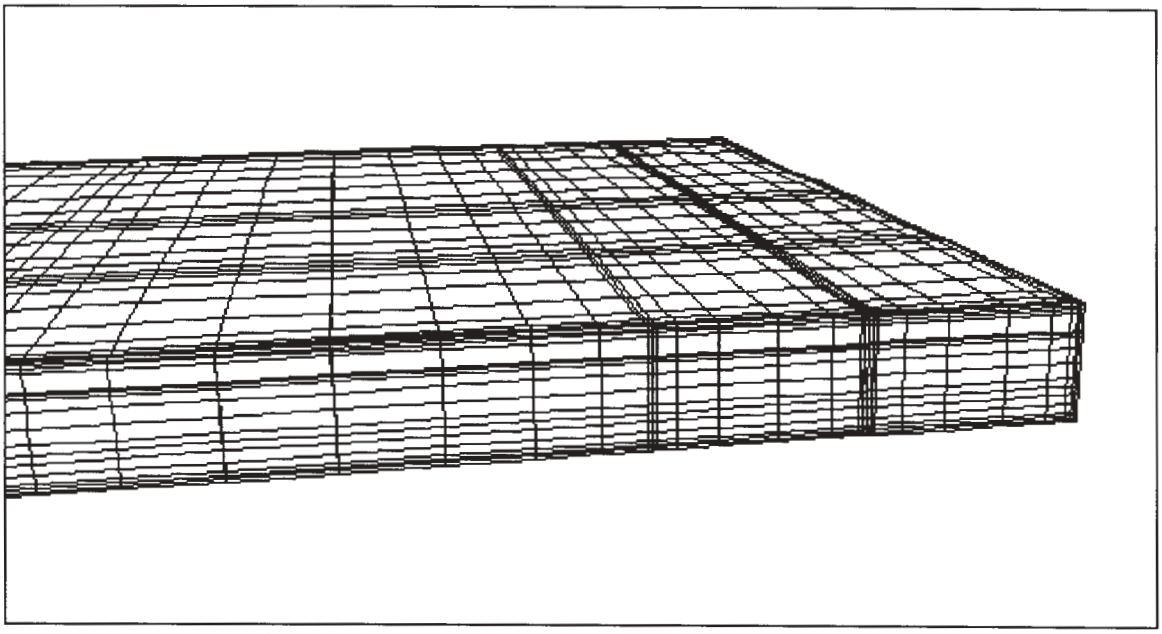


Figure 4.3 Sub-division of the geometry (grid)

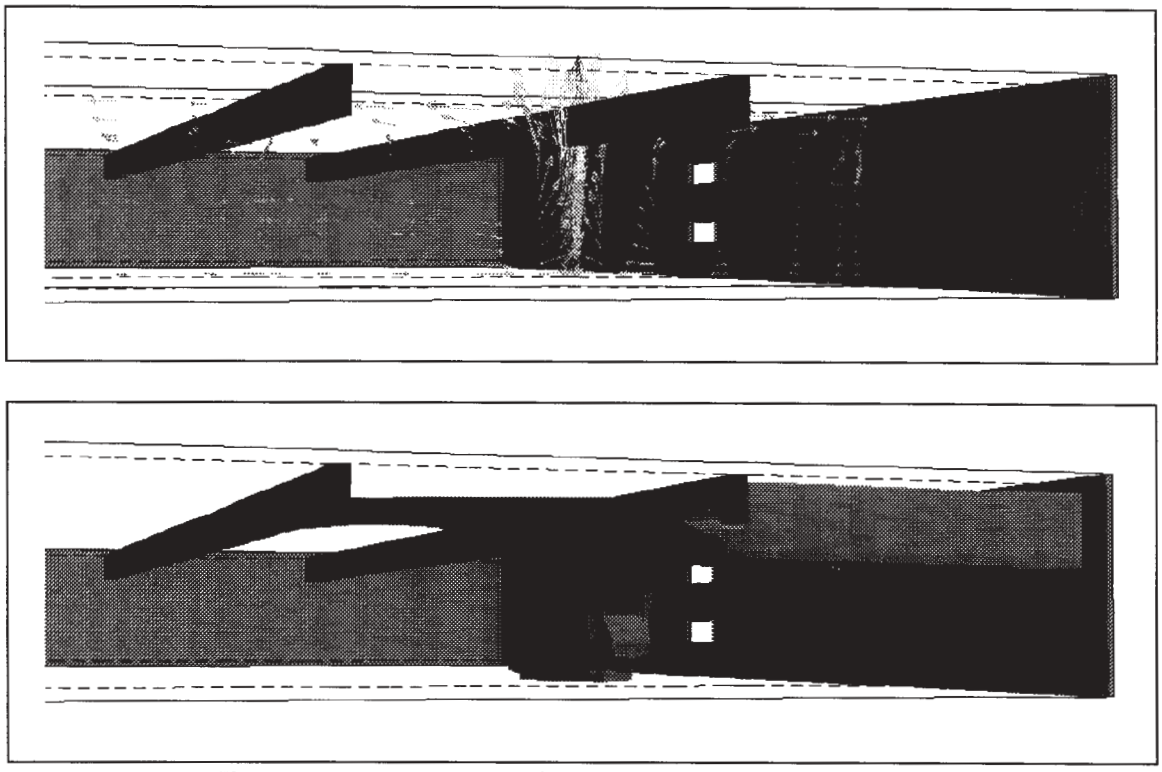


Figure 4.4 CFD modelization of natural convection

5 DATABASE OF NATURAL FIRE TESTS

5.1 INTRODUCTION

In order to be able to validate the air temperature field calculation methods, it was decided to collect data about natural fire tests. For the time being, the database contains 105 tests made in Australia, France, the Netherlands and UK. The complete database is given in annex 2. It can be summarised by the following table:

Test number in the Database	Reference NFSC	Number of Tests	Country	Date	RHR or mass loss measurement
1 to 6	4	6	Australia	1992	No
7 to 15	40	9	UK	1994	No
16 to 53	70	38	France	1973	Yes
54 to 63	71	10	France	1974	Yes
64 to 66	76	3	France	1993	Yes
67	182	1	France	1994	No
68	182 (Car test)	1	France	1995	Yes
69 to 71	275 to 277	*3*	*France*	*1996*	*Yes*
72 to 74	/	*3*	*NL*	*?*	*No*
75 to 78	/	*4*	*UK*	*1996*	*No*
79	278	1	France	1997	Yes
80	272	1	France	1994	Yes
81	273	1	France	1994	Yes
82	274	1	France	1994	Yes
83 to 105	U.K. Tests from B. Kirby	23	UK	1983 to 1986	No

plan_col.doc

It has to be pointed out that:

- the tests numbered 1 to 6 concern rather large compartments where the temperature is not uniform at all and that they have therefore not been used in our comparisons.
- the tests numbered 72 to 78 concern tests for which the data have not yet been provided by TNO. The tests numbered 72 to 74 have been performed in TNO and the tests numbered 75 to 78 are related to the eight storey building tests of - Cardington (2 natural fire tests have been performed by BRE and 2 by BSI).
- the tests numbered 83 to 105 refer to natural fire tests performed between 1983 and 1986 in Cardington by British Steel; unfortunately these tests can not been used because the final report is not yet published.

All the other tests are well documented and the test reports are available. The references of these reports are given herebelow.

NFSC4: "The Effect of Fire in the Office Building at 140 William Street Melbourne, Australia Thomas & Bennetts, BHP Research, Melbourne Laboratories, Tests June/July 1991.

NFSC40: "Natural Fires in Large Scale Compartments"; BST, FRS, B.R. Kirby.

NFSC71: Incendies naturels avec des meubles et du papier - Juillet 1974 - CTICM - WG3 meeting of the 10th of August 95 in Paris.

NFSC76: Essais d'incendie naturel avec profilés en acier nus et protégés - Etude de validation de modèles de développement du feu et de transfert thermique - Octobre 1993 - CTICM - WG3 meeting of the 10th of August 95 in Paris.

NFSC272: Rapport d'essai n° 94-E-157, Résistance au feu des éléments de construction, 19.04.1994, essai d'échauffement de structures extérieures en acier en cas d'incendie par bûcher à développement naturel, CTICM, France, F. Roy, H. Leborgne, O. Fréchet, 7.09.94.

NFSC273: Rapport d'essai n° 94-E-158, Résistance au feu des éléments de construction, 20.04.1994, essai d'échauffement de structures extérieures en acier en cas d'incendie par bûcher à développement naturel, CTICM, France, F. Roy, H. Leborgne, O. Fréchet, 7.09.94.

NFSC274: Rapport d'essai n° 94-E-346, Résistance au feu des éléments de construction, 22.09.1994, essai d'échauffement de structures extérieures en acier en cas d'incendie par bûcher à développement naturel, CTICM, France, H. Leborgne, O. Fréchet, 10.11.94.

NFSC275: Rapport d'essai n° 96-S-511, Résistance au feu des éléments de construction, Etude expérimentale d'un feu caractérisant un incendie survenant dans une chambre d'hôtel, 19.12.96 CTICM, France, H. Leborgne, O. Fréchet, 23.05.97.

NFSC276: Rapport d'essai n° 97-S-120, Résistance au feu des éléments de construction, Etude expérimentale d'un feu caractérisant un incendie survenant dans une chambre d'hôtel, 19.03.97 CTICM, France, H. Leborgne, O. Fréchet, 29.09.97.

NFSC277: Rapport d'essai n° 97-S-031, Résistance au feu des éléments de construction, Etude expérimentale d'un feu caractérisant un incendie survenant dans une lingerie d'hôtel et se propageant à un bureau, 04.02.97 CTICM, France, H. Leborgne, O. Fréchet, 01.10.97.

NFSC278: Rapport d'essai n° 97-E-417, Résistance au feu des éléments de construction, essai d'échauffement de structures extérieures en acier en cas d'incendie par bûcher à développement naturel, CTICM, France, H. Leborgne, O. Fréchet, 17.12.97.

5.2 DATABASE DESCRIPTION

The Database is an Excel file composed of different "Excel sheets". Each sheet corresponds to one test and contains the data such as:

- **Administrative information** including the number of test report, the NFSC number, the laboratory which has provided the report, the name of the publication, the date of the test, the laboratory which has made the test and a very short description of the contents of the report.

- **The geometry of the compartment** including the internal width W, the internal length D, the internal height H, the number of openings, the height h_i, the width w_i and the sill G_i of the openings. The convention considered for the position of the walls and for the distances W and D are given on the Figure 5.1.

- The description and the dimensions of the **walls** including the thickness of the layers, the material type, ρ, c and λ. The conventions considered for the position of the walls and the layers of the walls are given on the Figure 5.1. Pay attention that the first layer is the layer in contact with the outside.

- **The fire** information such as the fire load distribution (uniform or concentrated), the fire load in kg of wood/m², the total fire load expressed in kg of wood. Concerning the total fire load, in case of a fire load composed of different materials types, it corresponds to the sum of all the weights of the different materials multiplied by the corresponding conversion factor. The conversion factor is the heat of combustion of the material divided by the one of the wood of which the theoretical value is equal to 19 MJ/m^2 (14 MJ/m^2 if the combustion factor m is considered). Another information is given concerning the type and number of thermocouples.

- The **results** including the measurements of the mean air temperature, the mean air temperature at the ceiling, the maximum air temperature, the minimum air temperature, the mass loss and the rate of heat release. Concerning the maximum air temperature, if this maximum temperature has been recorded by only one thermocouples, "one curve" is written beneath "t° max.", otherwise "envelope" appears. Concerning the rate of heat release, either it has been deduced by the mass loss measurement or, in a few cases, it has been measured by oxygen depletion. In case of measurement by oxygen depletion, the conversion factor is given in the Fire definition.

The above-mentioned data are provided as an example for the test n°54 in the four following sheets.

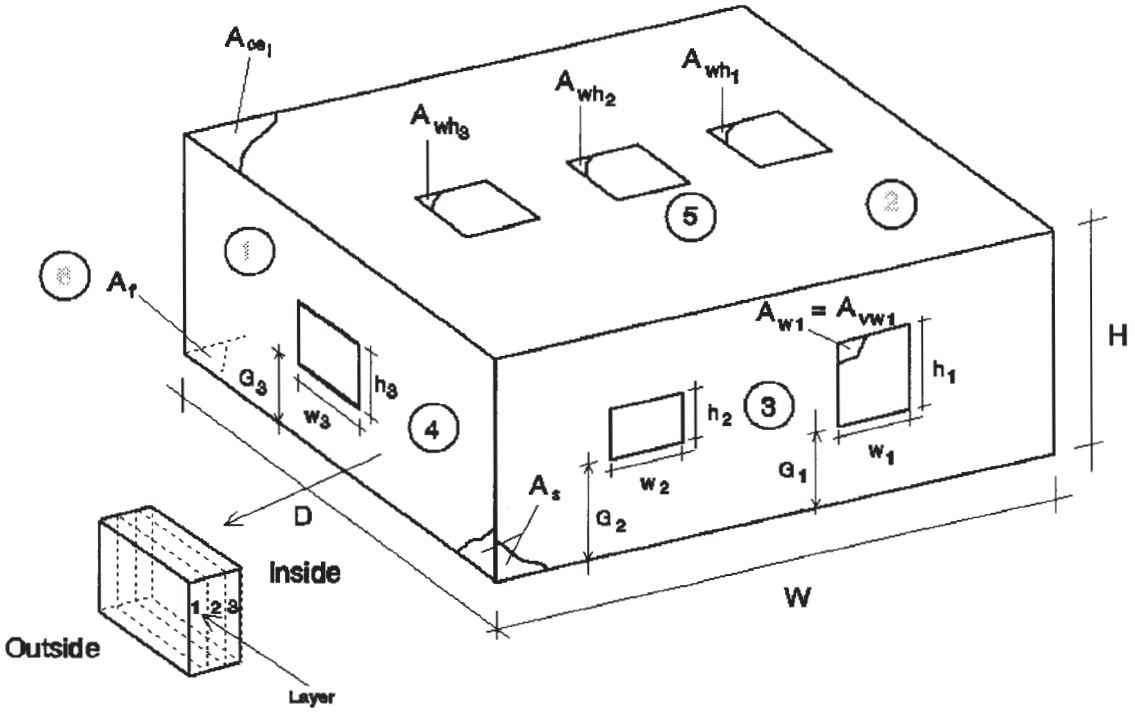


Fig. 5.1

notation.drw

Figure 5.1

Administrative Information

Test report N°	2.10.20-3	*Report Date*	jui-74	***NFSC Number*** 71	***Input Number*** 54
Received from	CTICM (FRANCE)				
Publication	" Incendies Naturels avec des Meubles et du Papier " exécutés dans la petite installation de Maizières-lès-Metz. P. Arnault , H. Ehm , J. Kruppa.				
Date of the Test		*Test n°*	123		
Laboratory	Centre Technique Industriel de la Construction Métallique.				
Short Description:	Influence of the ventilation and quantity of fire load on fires evolution. Study of non-insulated room with uniform fire load.				

Geometry of the Compartment

internal Width W [m]	3,36
internal Length D [m]	3,60
internal Height H [m]	3,13

Openings	*Height hi [m]*	*Width wi [m]*	*Sill Gi [m]*	*Wall N°*
1	1,06	0,90	2,07	4
2				
3				
4				
5				
6				

Walls

Wall N°1	*Thickness (cm)*	*material type*	rho (kg/m³)	c (J/kg K)	lambda (W/m K)
Layer 1	11,50	normal brick	1600	840	0,69
Layer 2	3,00	Vermiculite	200	1850	0,2
Layer 3					
Layer 4					

Wall N°2	*Thickness (cm)*	*material type*	rho (kg/m³)	c (J/kg K)	lambda (W/m K)
Layer 1	11,50	normal brick	1600	840	0,69
Layer 2	3,00	Vermiculite	200	1850	0,2
Layer 3					
Layer 4					

Wall N°3	*Thickness (cm)*	*material type*	rho (kg/m³)	c (J/kg K)	lambda (W/m K)
Layer 1	11,50	normal brick	1600	840	0,69
Layer 2	3,00	Vermiculite	200	1850	0,2
Layer 3					
Layer 4					

Wall N°4	*Thickness (cm)*	*material type*	rho (kg/m³)	c (J/kg K)	lambda (W/m K)
Layer 1	20,00	cellular concrete	450	1000	0,3
Layer 2					
Layer 3					
Layer 4					

Ceiling (wall n°5)	*Thickness (cm)*	*material type*	rho (kg/m³)	c (J/kg K)	lambda (W/m K)
Layer 1	20,00	cellular concrete	450	1000	0,3
Layer 2					
Layer 3					
Layer 4					

Floor (wall n°6)	*Thickness (cm)*	*material type*	rho (kg/m³)	c (J/kg K)	lambda (W/m K)
Layer 1	13 ?	refractory concrete	2300	1000	1,6
Layer 2					
Layer 3					
Layer 4					

Fire					Input Number	54
Fire load distribution (uniform or concentrated)			: uniform			
Fire load [kg of wood/m²]	30,0		Total Fire load [kg of wood]	295,3		

Material type	kg	Conv Factor
furniture	190	1
paper	162	0,53
pine laths	20	1

Thermocouples	
Type	
Number	10
Measurements:	

Results

Time [min]	° mean [°C]	t° mean at the ceiling	t° max [°C] Enveloppe	t° min [°C]	Mass lost [kg of wood]	RHR [kg of wood/sec]
0,00	20				0,00	0,00000
5,00	124				2,30	0,00768
10,00	88				4,61	0,00768
15,00	71				9,22	0,01536
20,00	149				20,74	0,03840
25,00	278				32,26	0,03840
30,00	384				55,30	0,07680
32,50	475				76,04	0,13827
35,00	580				129,03	0,35328
37,50	750				154,38	0,16898
42,00	940				179,73	0,09389
45,00	873				193,55	0,07677
50,00	712				207,37	0,04608
55,00	608				218,89	0,03840
60,00	552				228,11	0,03072
65,00	511				237,33	0,03072
70,00	477				244,24	0,02304
75,00					253,46	0,03072
80,00					260,37	0,02304
95,00						
100						
105						
110						
115						
120						
125						
130						
135						
140						
145						
150						
155						
160						
165						
170						
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185						
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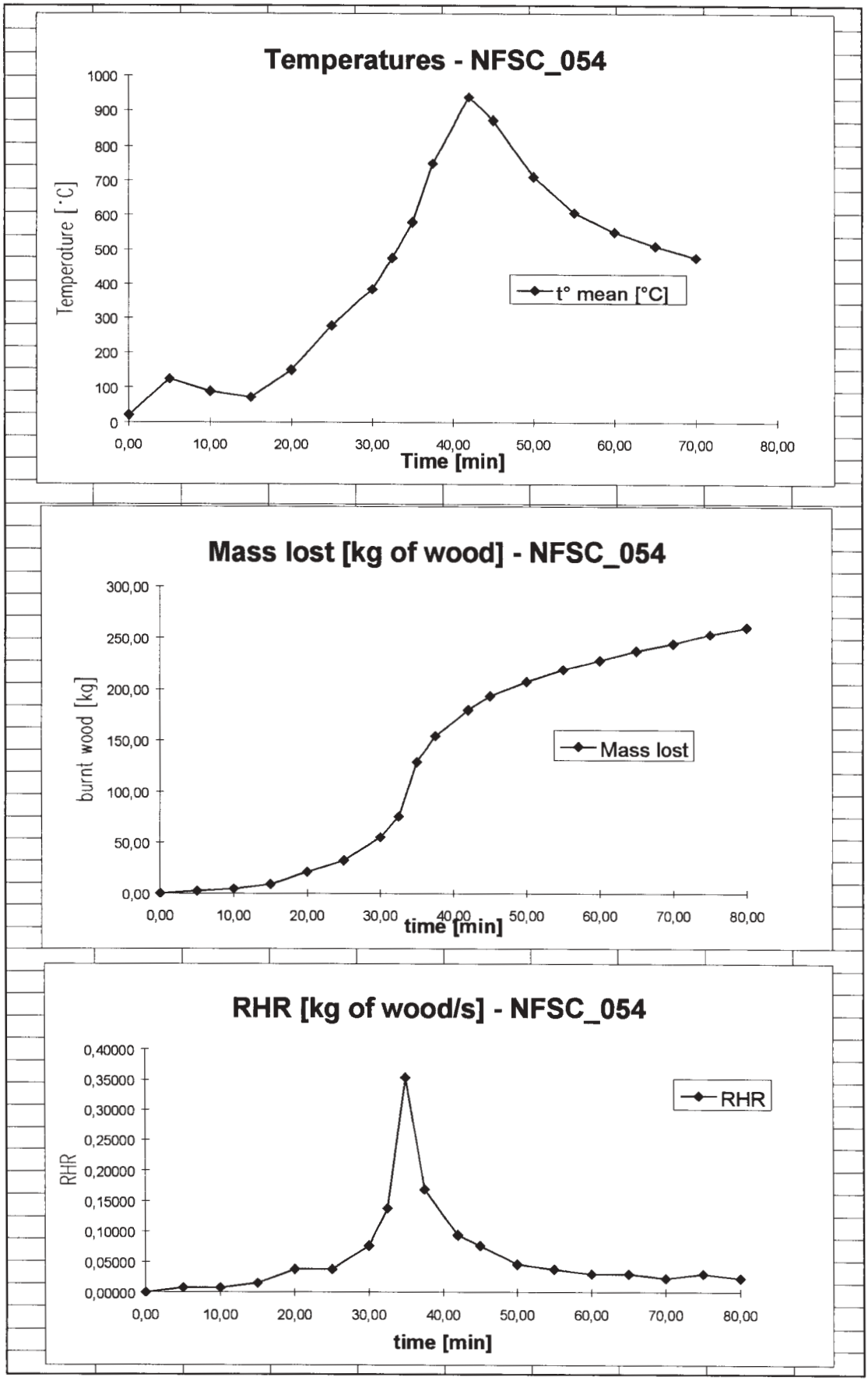
195						
200						
205						
210						
215						
220						
225						
230						
235						
240						


Temperatures - NFSC_054
Temperature [°C]
1000
900
800
700
600
500
400
300
200
100
0
0,00
10,00
20,00
30,00
40,00
50,00
60,00
70,00
80,00
Time [min]
t° mean [°C]
Mass lost [kg of wood] - NFSC_054
burnt wood [kg]
300,00
250,00
200,00
150,00
100,00
50,00
0,00
time [min]
Mass lost
RHR [kg of wood/s] - NFSC_054
RHR
0,40000
0,35000
0,30000
0,25000
0,20000
0,15000
0,10000
0,05000
0,00000
time [min]
RHR

5.3 OVERVIEW OF THE TESTS OF THE DATABASE

In fact **69** tests can be used now to compare with the results of a one zone model like Ozone.

These have been performed in the **CTICM** fire laboratory of Maizières-les-Metz in France and in the **BRE** fire laboratory of Cardington in UK.

The **dimensions** of the fire compartment are given in Figures 5.2 and 5.3. The maximum volume is 35 m^3, the maximum surface is 128 m^2, the maximum height is 3,13 m (the tests 83 to 105 are not considered for the time being).

The **openings** are always in only one wall. There is no horizontal opening in any test.

The **fire load** in the tests consists of wood cribs, real furniture, paper or even car. The fire load density was equal to 30 kg of wood/m^2 in more than half of the tests. One test was performed with a fire load of 90 kg of wood/m^2. The fire load density distribution for all the tests of the database is given on the Figure 5.4.

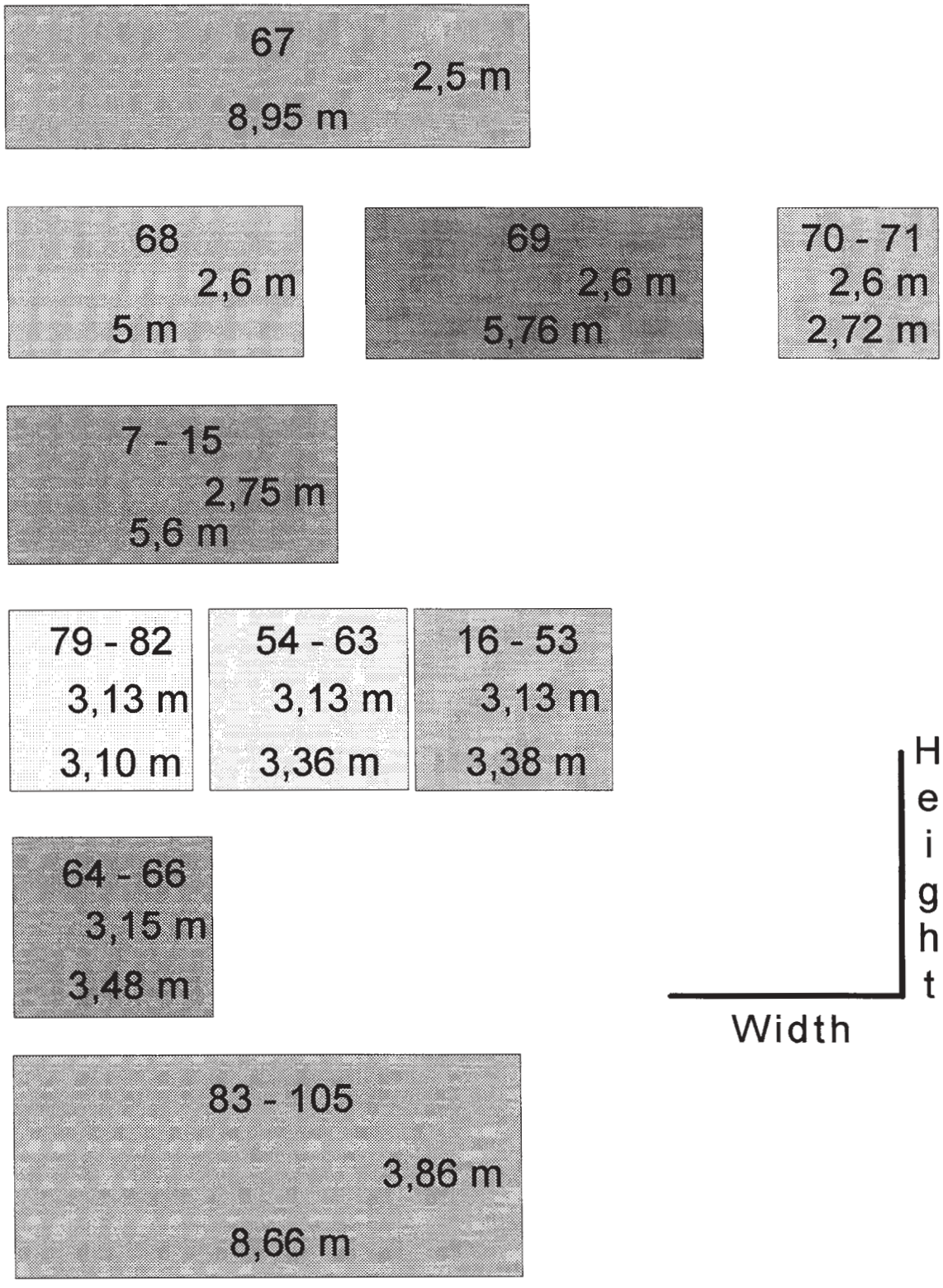

67
2,5 m
8,95 m
68
2,6 m
5 m
69
2,6 m
5,76 m
70 - 71
2,6 m
2,72 m
7 - 15
2,75 m
5,6 m
79 - 82
3,13 m
3,10 m
54 - 63
3,13 m
3,36 m
16 - 53
3,13 m
3,38 m
64 - 66
3,15 m
3,48 m
83 - 105
3,86 m
8,66 m
Height
Width

Figure 5.2

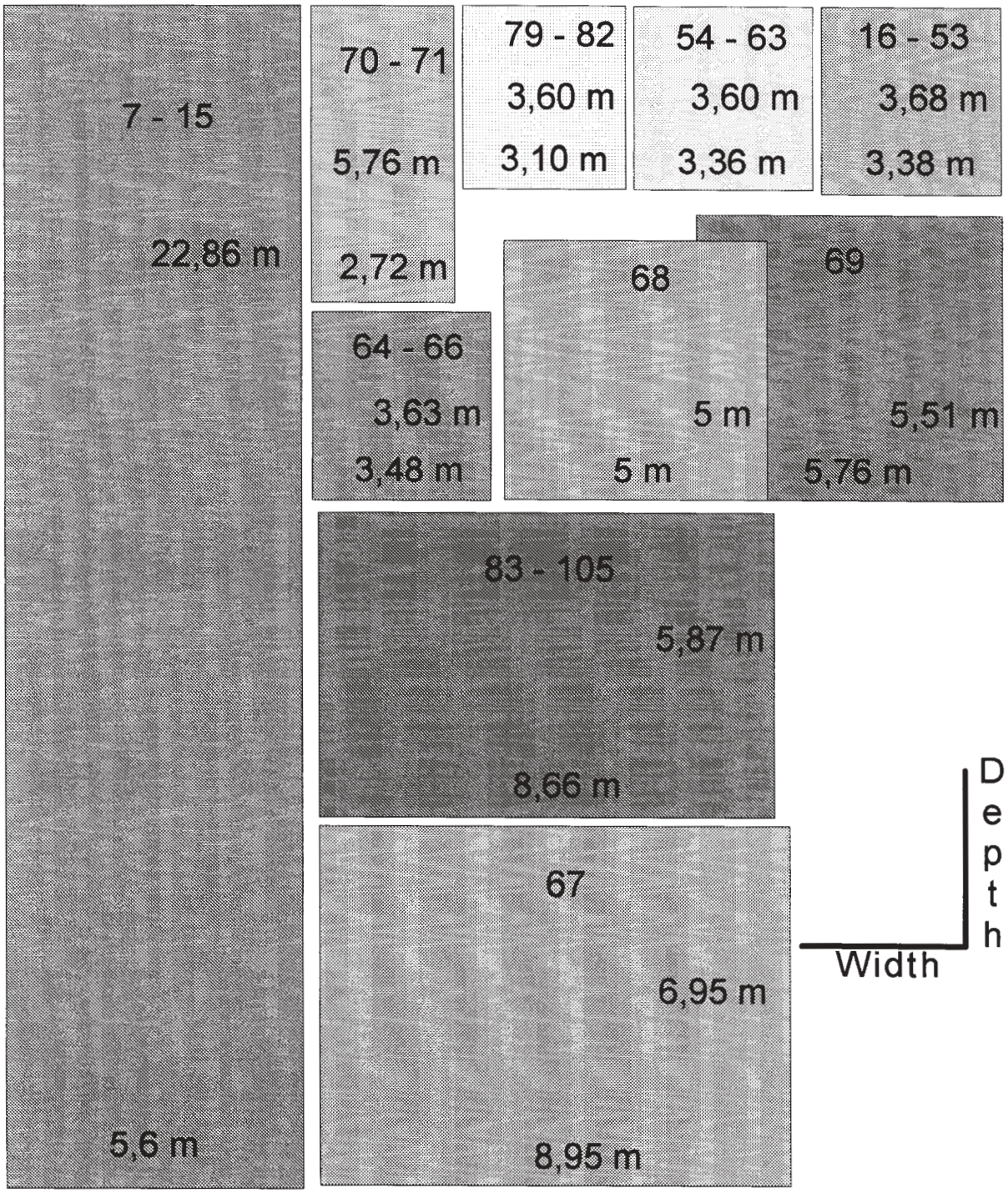

7 - 15
22,86 m
5,6 m
70 - 71
5,76 m
2,72 m
79 - 82
3,60 m
3,10 m
54 - 63
3,60 m
3,36 m
16 - 53
3,68 m
3,38 m
64 - 66
3,63 m
3,48 m
68
5 m
5 m
69
5,51 m
5,76 m
83 - 105
5,87 m
8,66 m
67
6,95 m
8,95 m
Depth
Width

Figure 5.3

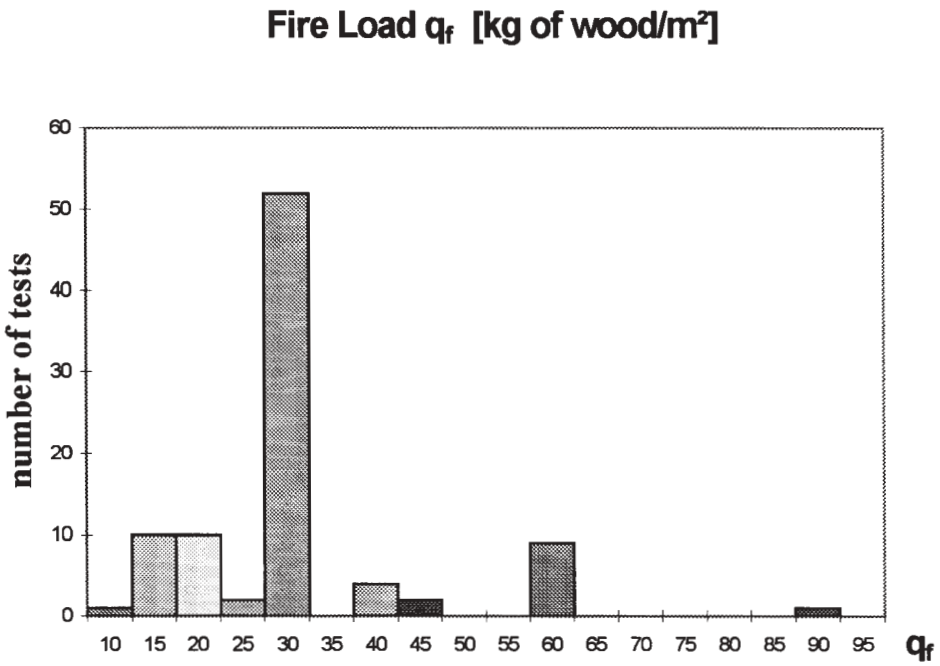

Fire Load q_f [kg of wood/m²]
number of tests
60
50
40
30
20
10
0
10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95
q_f

Figure 5.4

6 THE ONE ZONE MODEL OZONE - DESCRIPTION AND VALIDATION BASED ON 54 EXPERIMENTAL FIRE TESTS

6.1 INTRODUCTION

Zone models are numerical tools commonly used for the evaluation of the temperature development of the gases within a compartment during the course of a fire. Based on a limited number of hypotheses, they are easy to use and provide a good evaluation of the situation provided they are used within their real field of application. Since the first numerical one zone models have been made by Petersson, major developments of the numerical fire modelling have been done. Among other things, multi-zones and computational field dynamics models have been developed. Although one zone model is the less sophisticated numerical fire model, it has its own field of application and thus is an essential tool in fire safety engineering applications.

The main hypothesis in zone models is that the compartment is divided in zones in which the temperature distribution is uniform at any time. In one zone models, the temperature is considered to be uniform within the whole compartment. This type of model is thus valid in case of fully developed fires, contrary to multi zones models which are valid in case of localised fires. In this last type of model there are a hot layer which is close to the ceiling and a cold layer which is close to the floor.

The aim of this chapter is to present on one hand a new one zone model called "OZone" and on the other hand its validation on full scale fire tests.

In OZone several improvements on existing one zone models have been made. The basic equations of the model have been written considering that the specific heat of the gas in the compartment is a function of the temperature. The wall model is made by the finite element method and is implicit. And finally different combustion models have been developed to cover different situations of use of the code.

This one zone model has been developed in the scoop of the ECCS research "Natural Fire Safety Concept". Within the same research a database of natural fire tests has been created (see chapter 5). The code has been validated on 54 tests of this database and a comparison of OZone and another one zone model NAT has been made.

A Graphic User Interface has been developed to define the input data.

6.2 ZONE MODEL

Numerical one zone models are normally based on six physical variables. These variables are linked by four constraints and two differential equations describing the mass and the energy balance in the compartment. The time integration of these differential equations allows to calculate the evolution of the variables describing the gas in the compartment. The mass balance equation expresses the fact that, at any moment, the variation of the mass of the gas inside the compartment is equal to the mass of combustion gases created by the fire, plus the mass coming into the compartment through the openings minus the mass going out of the compartment through the vents. The energy balance equation expresses the fact that, at any moment, there is a balance between, on one hand, the energy which is produced in the compartment by the combustion and, on the other hand, the way in which this energy is consumed: by the heating of the gases in the compartment, by the mass loss of hot air through the openings (including a negative term accounting for the energy of incoming air), by the radiation loss through the openings and, finally, by the heating of the walls. It has to be mentioned that the term "*wall*" is used here to represent all the solid surfaces of the enclosure of the compartment, namely the true vertical walls, the floor and the ceiling.

The six variables which are considered to describe the gas in the compartment are: m, the mass of the gas; T, the temperature of the gas; V, the volume of the compartment (constant); E, the internal energy; p, the pressure in the compartment; ρ, the gas density.

The four constraints are:

$$\rho = \frac{m}{V}$$
$$E = c_V(t) m T$$
$$p_0 = \rho R T \qquad (6.1)$$
$$V = const.$$

with $c_V(T)$, the specific heat of the gas in the compartment;
R, the gas constant

The mass balance equation has the general form of equation 6.2 in which a doted variable $\dot{x}$ means the derivative of x with respect to time. Equation 6.2 states that the variation of gaseous mass in the compartment is made of the difference between the mass coming in and the mass going out through the openings, plus the mass of combustion products generated by the fire. $\dot{m}_f$ can therefore be seen as the mass transformed at every moment from a solid form to gaseous product by the pyrolisis.

$$\dot{m} = \dot{m}_{in} - \dot{m}_{out} + \dot{m}_f \qquad (6.2)$$

The energy balance equation has the general form of equation 6.3 stating that the variation of energy in the compartment is made of the energy release by the fire, i.e. the rate of heat release (RHR) minus the loss of energy by radiation through the openings ($\dot{Q}_{opening}$), to and through the wall $\dot{Q}_{wall}$ and in the air going out of the compartment $c_p(T_{out})\dot{m}_{in}T_{out}$ or entering the compartment $c_p(T)\dot{m}_{out}T$.

$$\dot{q} = RHR - \left(\dot{Q}_{opening} + \dot{Q}_{wall} + c_p(T)\dot{m}_{out}T - c_p(T_{out})\dot{m}_{in}T_{out}\right) \tag{6.3}$$

The energy transmitted at the interface between the compartment and the wall has the form of equation 6.4 in case of a heat transfer by convection and radiation if we note T_{w1} the temperature at the surface of the wall.

$$\dot{Q}_{wall} = h(T - T_{w1}) + \sigma\varepsilon^*\left(T^4 - T_{w1}^4\right) \tag{6.4}$$

Two basic variables have to be chosen to describe the system. Provided that the temperature T and difference of pressure from the initial time Δp are chosen, equations 6.1 and 6.2 can be transformed in the system of ordinary differential equations formed by equations 6.5 and 6.6.

$$\dot{\Delta p} = \frac{\dot{q} + \dot{m}\rho T^2 \dfrac{dc_p(T)}{dT}}{\dfrac{V}{\gamma - 1} + \dfrac{TV}{R}\dfrac{dc_p(T)}{dT}} \tag{6.5}$$

$$\dot{T} = \frac{1}{c_p(T)\rho V}(\dot{q} - c_p(T)\dot{m}T + V\dot{\Delta p}) \tag{6.6}$$

with $\gamma = \dfrac{c_p}{c_v}$

The variation of the specific heat of the gas with the temperature is taken into account by the following relation:

$$\mathbf{c_p(T) = 0{,}187\ T + 952\ [J/(kg\ K)]} \tag{6.7}$$

This law is obtained by a linear regression on the law given in the Handbook of Fire Protection Engineering.

The system of equations 6.5 and 6.6 is stiff because the time constant relative to the pressure variation is much shorter than the time constant of the temperature variation. It is therefore usual to rely on a specialised library solver specifically written for this kind of problem. In the code OZone, the solver DEBDF is used.

6.3 WALL MODEL

During the development of the OZone code in Liege, it was decided that the wall model should be such that the energy balance is fully respected. That is only possible if the wall temperatures are solved implicitly.
First of all, the wall was discretised by a finite element model as depicted in Figure 6.2. With this discretisation, the temperature is computed at the interface between the different layers, or elements, and the hypothesis is made of a linear temperature variation on the thickness of each layer.

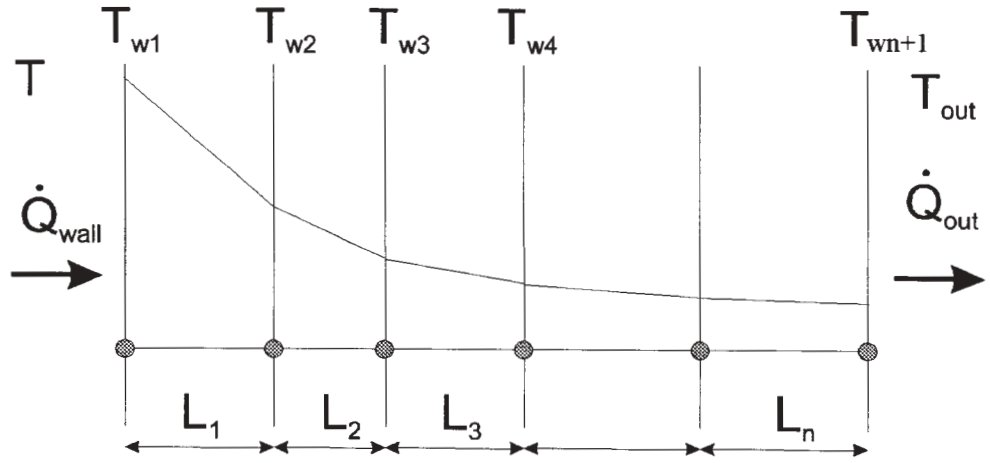


Figure 6.1 : discretisation by finite elements

With this discretisation and this hypothesis on the field of temperature, well known developments show that the equilibrium of each finite element **i** is described by the following equation:

$$\mathbf{K}_{el,i}\,\mathbf{T}_{el,i} + \mathbf{C}_{el,i}\,\dot{\mathbf{T}}_{el,i} = \mathbf{g}_{el,i} \tag{6.8}$$

with $$\mathbf{T}_{el,i} = \begin{Bmatrix} T_{wi} \\ T_{wi+1} \end{Bmatrix} \tag{6.9}$$

$$\mathbf{K}_{el,i} = \frac{k_i}{L_i}\begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \tag{6.10}$$

$$\mathbf{C}_{el,i} = \mathbf{c_i}\,\rho_i\,\mathbf{L_i}\begin{bmatrix} \mathbf{0,5} & \mathbf{0} \\ \mathbf{0} & \mathbf{0,5} \end{bmatrix} \tag{6.11}$$

and $$\mathbf{g}_{el,1} = \begin{Bmatrix} \dot{Q}_{wall} \\ 0 \end{Bmatrix} \;;\; \mathbf{g}_{el,2}\ to\ \mathbf{g}_{el,n-1} = \begin{Bmatrix} 0 \\ 0 \end{Bmatrix} \;;\; \mathbf{g}_{el,n} = \begin{Bmatrix} 0 \\ \dot{Q}_{out} \end{Bmatrix} \tag{6.12}$$

Equations 6.10 and 6.11 are in fact simplified expressions because the material properties have been considered as constant in each element, allowing to take them as constant multipliers out of the matrix. The temperature dependency in the element could also be taken into account, owing to the well known numerical integration techniques of Gauss. Equation 6.11 is furthermore the diagonalised version of the complete matrix, having a value of 1/3 for the diagonal terms and 1/6 for the off diagonal terms. The advantage of the diagonal form is first that it smooths the spatial oscillations which could arise in the solution if too thick elements are used in the discretisation. Another advantage is related to the computing strategy, as will be explained in the formulation of equation 6.15.

The assembly of the N equations of type 8 which can be written for each of the N finite element making the wall produce the system of equations 6.13 in which the size of the vectors is N+1 and (N+1) x (N+1) for the matrices.

$$\mathbf{K}\,\mathbf{T}_w + \mathbf{C}\,\dot{\mathbf{T}}_w = \mathbf{g} \tag{6.13}$$

$$\text{with} \quad \mathrm{g} = \begin{Bmatrix} \dot{Q}_{wall} \\ 0 \\ \\ 0 \\ \dot{Q}_{out} \end{Bmatrix} \tag{6.14}$$

From the system of equations 6.13, it is very easy to obtain the system of equations 6.15, efficiently computed owing to the diagonal nature of **C**.

$$\dot{\mathbf{T}}_w = \mathbf{C}^{-1}\left(\mathbf{g} - \mathbf{K}\,\mathbf{T}_w\right) \tag{6.15}$$

This system of equations is a set of N differential equations for the N temperatures of the wall. The temperature of the compartment is only present in the first term of the load vector, see equations 6.4 and 6.14. It has a similar form as the system of equations 6.5 and 6.6 established for the 2 variables of the compartment and could be written in the following way.

$$
\begin{aligned}
\dot{T}_{w1} &= g_1(T, T_{w1}, T_{w2}) \\
\dot{T}_{w2} &= g_2(T_{w1}, T_{w2}, T_{w3}) \\
&\cdot \\
\dot{T}_{wi} &= g_i(T_{wi-1}, T_{wi}, T_{wi+1}) \\
&\cdot \\
\dot{T}_{wN} &= g_N(T_{wN-1}, T_{wN}, T_{out})
\end{aligned}
\qquad (6.16)
$$

6.4 CONNECTION OF THE ZONE MODEL AND THE WALL MODELS

Equations 6.5, 6.6 and 6.16 form a set of N+2 differential equations which can be passed on to the numerical solver. This one will integrate the equations taking into account the coupling between the compartment and the wall and solving the N+2 variables which are the pressure variation and the temperature in the compartment, plus the temperatures at every node of the wall. If one considers that the usual procedure sets the limits of the compartment on the inside surface of the wall and adds a wall submodel on top of it, the proposed procedure amounts in fact to set the limit of the compartment on the outside surface of the wall. Because all the equations are solved simultaneously with an implicit procedure, the energy balance between the gas and the wall is totally respected.

If the enclosure has M different types of walls, the system of equations 6.15 has to be build M times. If N_i-1 is the number of element of the wall n°i, the total set of equations contains $\sum_{i=1}^{M} N_i + 2$ differential equations.

6.5 EXCHANGES THROUGH THE OPENINGS

The mass flow through vents is calculated by integrating the Bernoulli's law on each opening.

If the altitude where the pressure inside the compartment is equal to the pressure outside of the compartment is in an opening, the openings is divided in two parts, one where the mass flow goes inside the compartment and another one where the mass flow goes outside.

The radiation through the windows is taken into account by the Stefan-Boltzmann law. One considers that the radiation exists only bellow the altitude where the pressure inside the compartment is equal to the pressure outside the compartment. Above this level the gases goes out of the compartment and the temperature outside (in the plume) is assumed to be equal to the temperature in the compartment and thus it is considered that the net radiation flux is equal to zero (Figure 6.2).

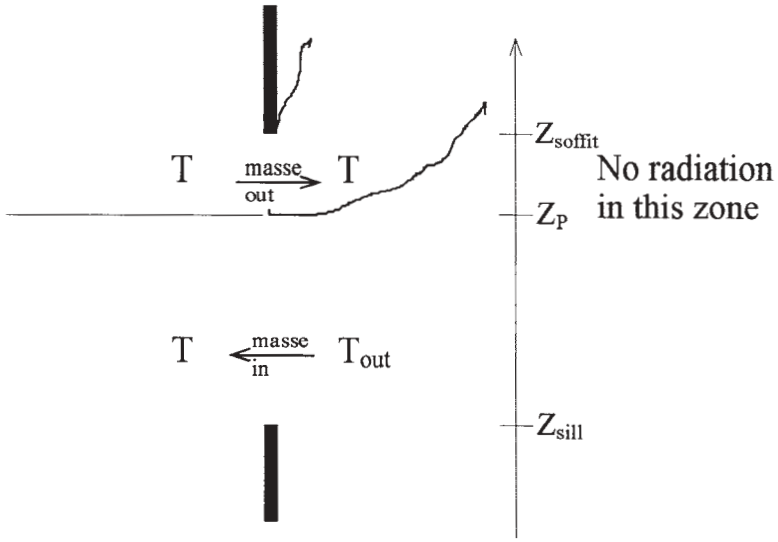


Figure 6.2 : Exchanges through openings

6.6 ENERGY RELEASE BY THE FIRE

The basic input data are the pyrolisis rate $\dot{m}_f$ [kg/s] and the heat of combustion of the fuel H_f [J/kg]. Moreover users of OZone must choose between the three different combustion models. Each of them has been designed to represent a different situation of utilisation of the code.

6.6.1 COMBUSTION MODEL 0 (CM0)

If the pyrolysis rate and the RHR are known function of time, no modification by the code is made. This case corresponds to the simulation of test where the mass loss and the rate of heat release have been measured.

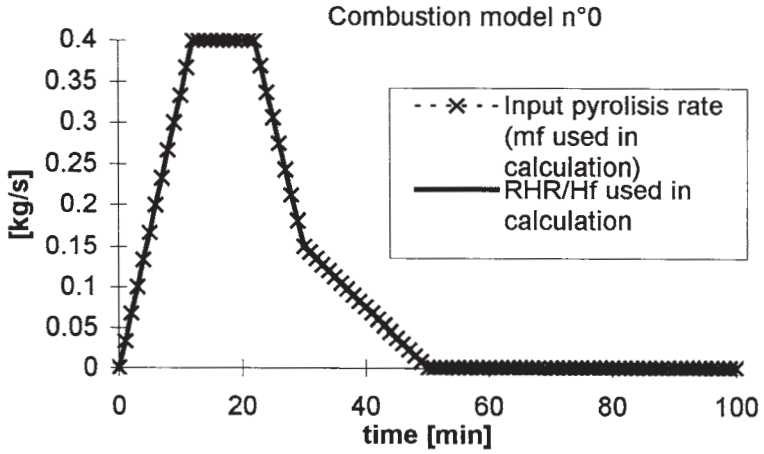


Figure 6.3

6.6.2 COMBUSTION MODEL 1 (CM1)

When using this model, the release of energy may be limited by the quantity of oxygen available in the compartment. The mass loss is unchanged. If $\dot{m}_f$ and the heat of combustion of fuel H_f [J/kg] are known, but the rate of heat release is unknown, this combustion model has to be used. The following chemical reaction is considered:

1 kg of fuel + 1,27 kg of 0_2 = 2,27 kg of combustion products + H_fMJ (17)

And this procedure is used:

1. The mass of oxygen in the compartment is calculated at each time by integrating the oxygen balance:

$$\dot{m}_{ox} = \dot{m}_{ox,in} - \dot{m}_{ox,out} - 1{,}27\,\dot{m}_f \quad (18)$$

with m_{ox}: mass of oxygen in the compartment
$m_{ox,in}$: mass of oxygen coming in the compartment through openings
$m_{ox,out}$: mass of oxygen going out of the compartment through openings

2. If the mass of oxygen in the compartment is higher than 0kg, the fire is fuel controlled and all the mass loss of fuel delivers energy.

$$\dot{m}_f = \dot{m}_{f,input}$$
$$RHR = \dot{m}_f H_f \quad (19)$$

3. If all the oxygen in the compartment is consumed, the fire is ventilation controlled and the combustion is not complete. The energy released is governed by the mass of oxygen coming in the compartment:

$$\dot{m}_f = \dot{m}_{f,input}$$
$$RHR = \frac{\dot{m}_{ox,in}}{1{,}27} H_f \quad (20)$$

In this model an external combustion is assumed, all the fire load is transformed into gases in the compartment but only a part of it delivers energy in the compartment.

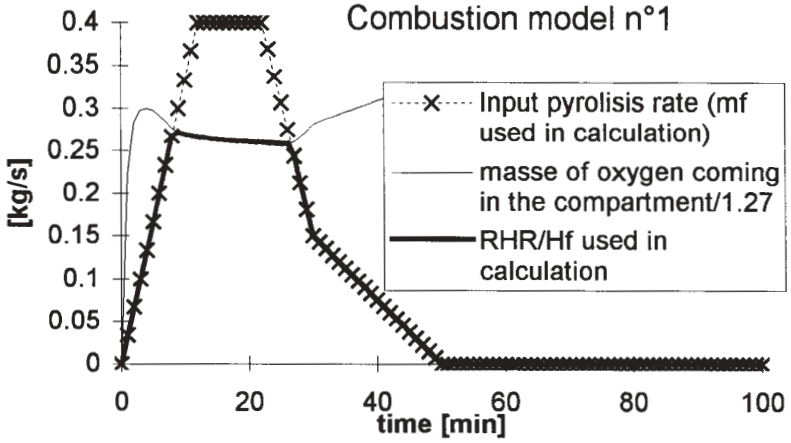


Figure 6.4

6.6.3 COMBUSTION MODEL 2 (CM2)

When using this model, the release of mass may be limited by the quantity of oxygen available in the compartment. This means that, at any time, equation 6.17 is respected. The quantity of mass released by the fire is always proportional (1/1,27) to the quantity of oxygen used by the fire. The total mass of fuel is burnt inside the compartment (safe procedure) then the fire duration is increased compared to the input one.

The following procedure is used.

1. The mass of oxygen in the compartment is calculated at each time by integrating the oxygen balance (mass of oxygen coming the compartment trough openings minus the mass going out minus the mass of O_2 used by the fire) :

$$\dot{m}_{ox} = \dot{m}_{ox,in} - \dot{m}_{ox,out} - 1{,}27\,\dot{m}_f$$

2. If the mass of oxygen in the compartment is higher than 0kg, the fire is fuel controlled and all the mass of burning material is transformed into energy.

3. If the mass of oxygen in the compartment is 0kg, the fire is ventilation controlled and the combustion is not complete. The mass lost by the fire is governed by the mass of oxygen coming in the compartment:

$$\dot{m}_f = \dot{m}_{f,vent} = \frac{\dot{m}_{ox,in}}{1{,}27}$$

$$RHR = \dot{m}_{f,vent} H_f$$

4. The linear decreasing phase begins when 70% of the total fire load is consumed.

In this model **no** external combustion is assumed, all the fire load delivers in energy into the compartment. The pyrolysis rate is controlled by the oxygen coming in the compartment.

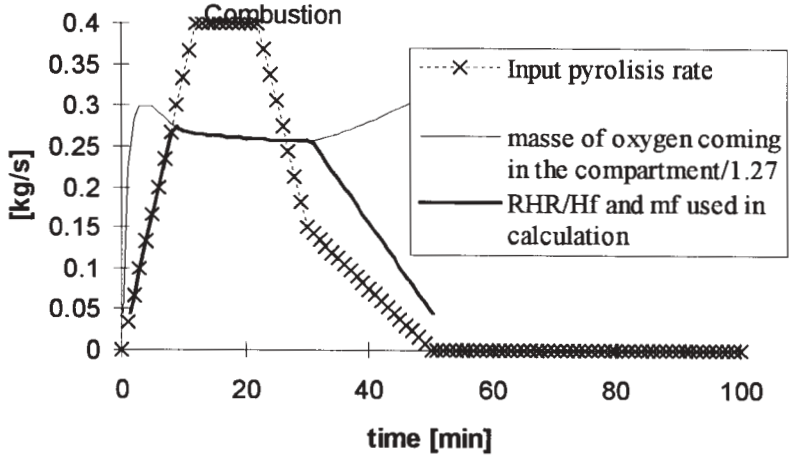


Figure 6.5

6.7 VALIDATION

6.7.1 COMPARISON WITH AN EXISTING CODE (NAT)

In this section, an academic example of application of the OZone code is presented and the results are compared with those of the one zone model NAT [XX]. This code was made at the CSTB in France and the calculations presented here were made by Daniel Joyeux from the CTICM, France.

The compartment has the following dimension: length 5 m; width 5 m; height 2,5 m. There is one opening of 1,4 m large and 1,9 m height, the sill is 0,4 m height. The walls (ceiling and floor included) are 20 cm thick and made of normal weight concrete. The rate of heat release is given at the Figure 6.4 and has a maximum of 4 MJ/s.

The temperature and the pressure of the gas in the compartment are given in Figures 6.6 & 6.7.

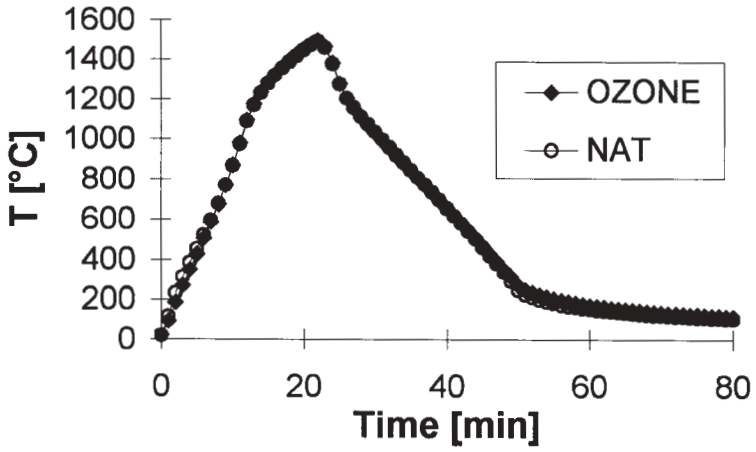


Figure 6.6: Temperature of gas

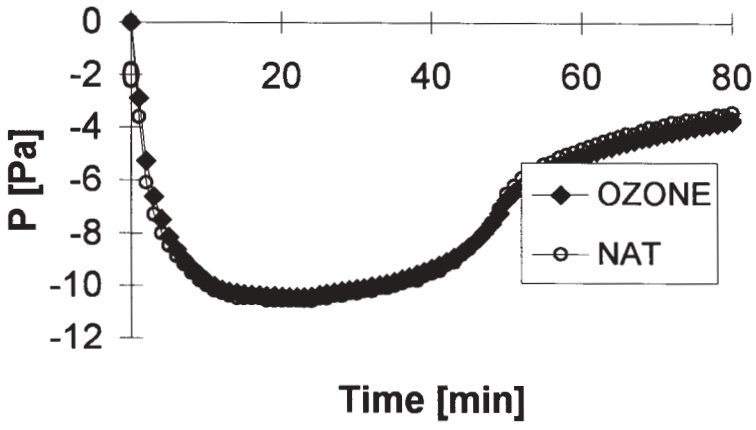


Figure 6.7: Pressure in the Compartment

The different terms of the energy balance are shown on Figure 6.8

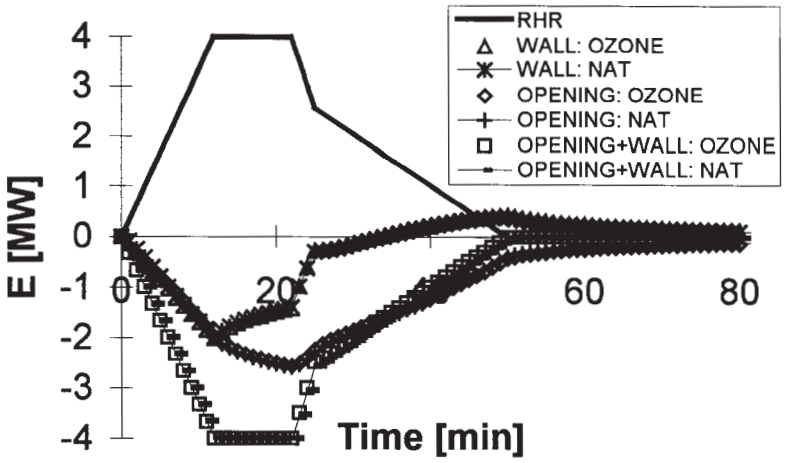


Figure 6.8 : Energy Balance

A very good agreement is found between the two codes.

6.7.2 COMPARISON WITH EXPERIMENTAL TESTS

The data base of experimental fire tests comprises more than 80 test results, 54 of them have been analysed up to now. In these tests, the fire load per total area of the enclosure varied between 37 and 151 MJ/m² whereas the opening factor varied between 0,015 and 0,157 $m^{0,5}$. Observation of the results showed that some tests lead to a fuel bed control regime whereas others were clearly ventilation controlled. When the pyrolisis rate or the Rate of Heat Release – RHR - had been measured during the test, it was introduced in the simulation and combustion model number 1 was activated ; lack of oxygen leads to a reduction of the RHR but the duration of the fire is not increased, which amount to assume external flaming. When only the fire load was known, a RHR curve was introduced, based on a t^2 growing phase, a constant release phase and a linear descending branch starting when 70 % of the fire load has been consumed. In the later case, the combustion model number 2 of OZone was activated; a lack of oxygen leads to a reduction of the RHR leading to a duration of the fire longer than the one assumed in the data.

Figure 6.9 gives a comparison of the maximum gas temperature as measured in the test and computed by the model. Each point is representative of a test and the oblique line is the location of the point giving a perfect fit. The doted line is the linear regression among all the points.

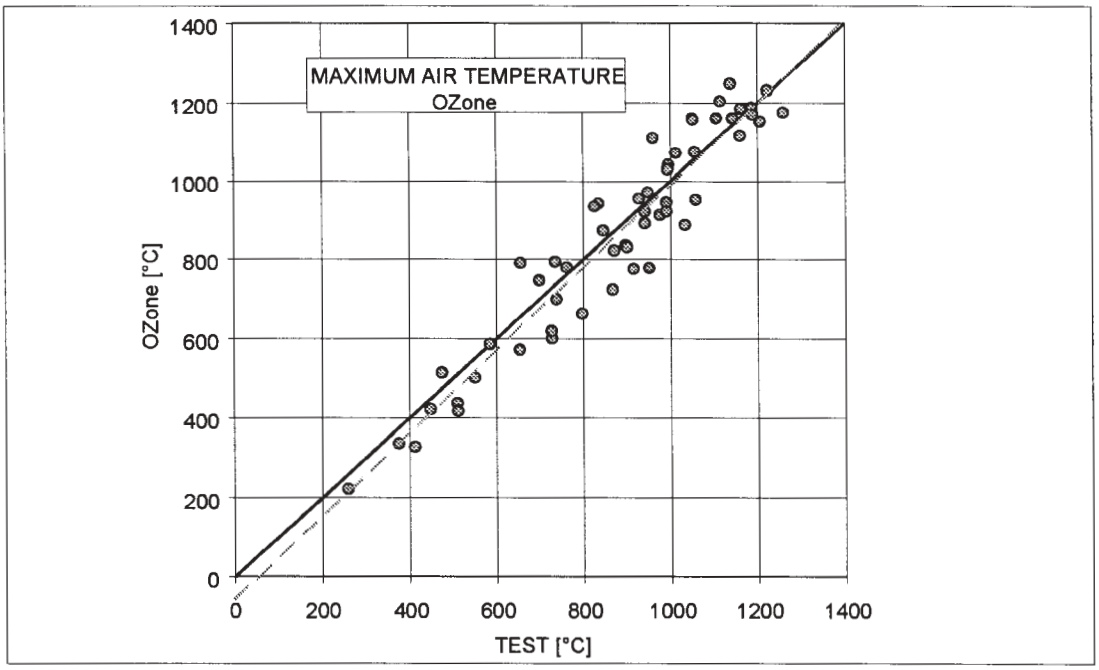


Figure 6.9 : maximum temperature in the compartment

The maximum gas temperature is yet only a scalar and may not be a sufficiently good indicator of the good fit between two curves. For each test, the temperature evolution was computed in a typical unprotected steel section – HEB200, U/F = 147 m^{-1} – first submitted to the recorded gas temperature, then submitted to the computed gas temperature. This allowed to draw Figure 6.10 where each test is represented by the maximum temperature in the unprotected steel section and where the agreement is also rather good.

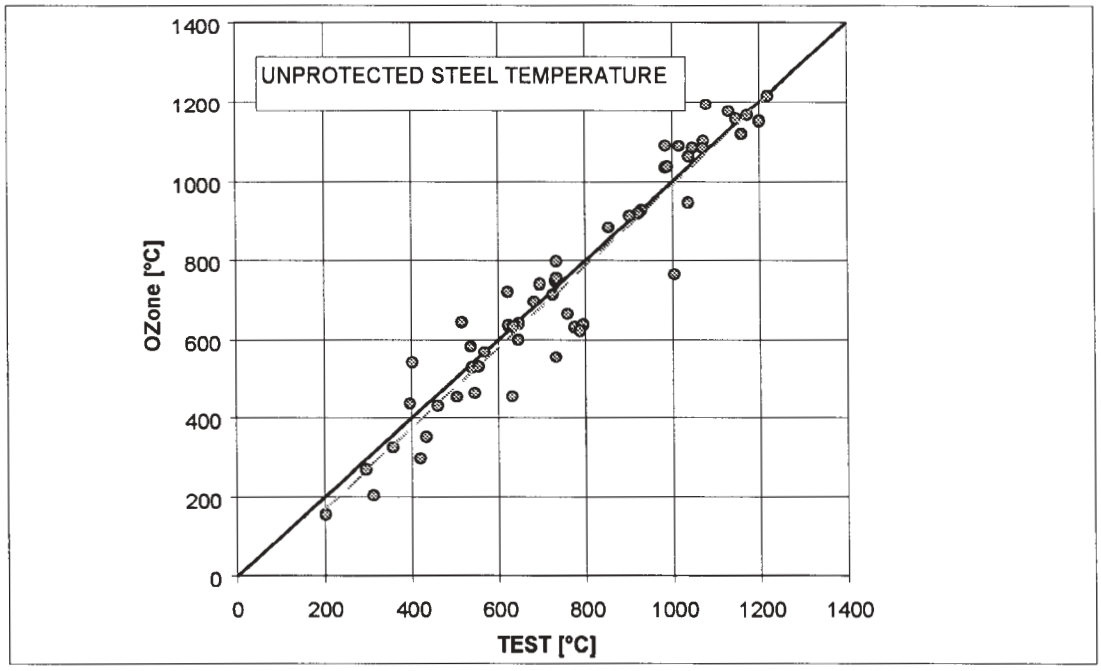


Figure 6.10 : maximum temperature in the unprotected steel section

The temperature in an unprotected steel section tends to follow the evolution of the gas temperature with a rather limited delay. The maximum steel temperature is therefore sensitive to the severity of the fire, much more than to the duration of the fire. With this in mind, another comparison was made, based on the maximum temperature computed in a *protected* steel section.

The same section was chosen but supposed to be protected by 20 mm of a dry material having a specific heat of 1850 J/kgK, a specific mass of 300 kg/m³ and a thermal conductivity of 0,20 W/mK. Figure 6.11 has been drawn with these values.

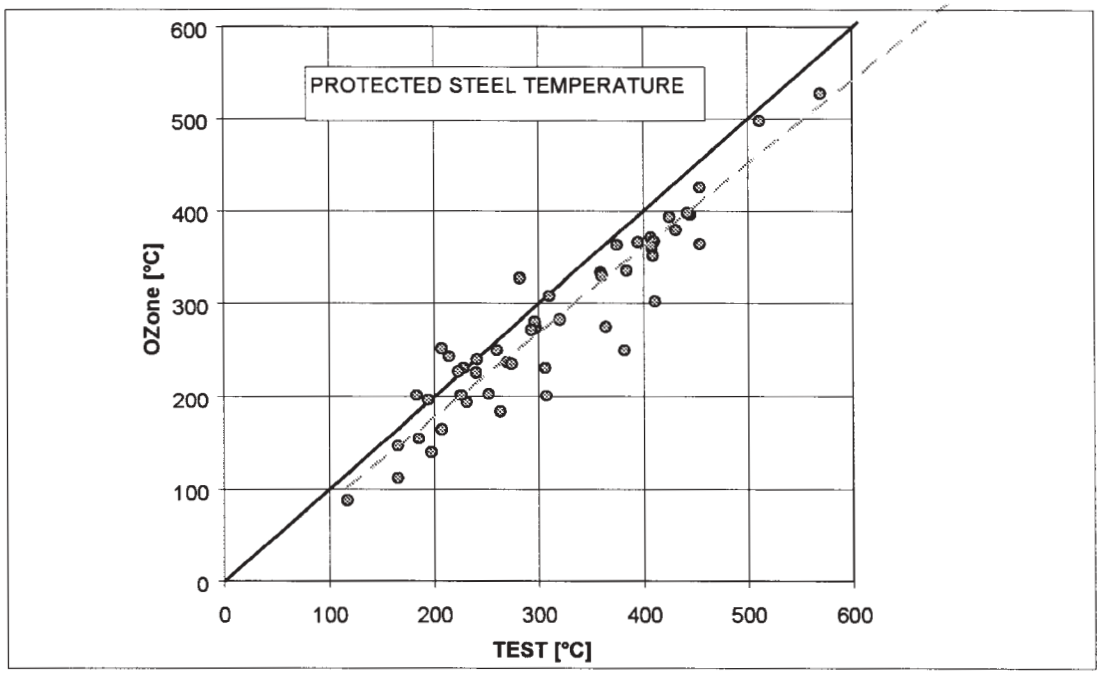


Figure 6.11 : maximum temperature in the protected steel section

Although the correlation is still very good, there seems to be a systematic trend for OZone to underpredict the protected steel temperatures by a factor of approximately 10 %. This was clearly traced to the fact that the temperatures of the gas decrease somewhat faster in the OZone simulation than in the experimental test. Although this should be confirmed experimentally, this could be due to the fact that the recorded experimental temperature is in fact the temperature of thermocouples placed in the compartment and that these thermocouples are influenced not only by the gas temperature but also by the radiation flux that they receive from the walls. The walls, cooling down slower than the gas, would then to some extend delay the cooling down of the thermocouples.

6.8 CONCLUSIONS

In the new one zone model OZone, the variation of the specific heat of the gas in the compartment is taken into account in the basic formulation of the equations.

The discretisation of the walls by a traditional finite element approach allows to formulate the differential equations which govern the heat transfer by conduction within the material. These equations can be added to the usual set of two differential equations describing the evolution of situation within the compartment. These two sets of equations can be solved simultaneously by the numerical solver. Because the two sets of equations are coupled by the temperature of the inside surface of the wall, the energy balance between the compartment and the wall is strictly respected.

This proposed procedure provides an elegant and robust way to account for the heat transfer to the walls that does not require the introduction of hypotheses on the time evolution of the interface temperature.

Three different combustion models have been introduced to allow the user to run the code for different purposes. The combustion models 0 and 1 are designed to model full scale fire tests. The CM1 can also be used in a design procedure if the duration of the fire is known or imposed by the user. The combustion model 2 has to be used in fire safety design procedures.

The comparison between OZone and NAT is very good. The agreement between experimental test results and results computed by a numerical code based on this procedure appears as quite satisfactory.

A Graphic User Interface has been developed to define the input data.

The code is available for free at the University of Liège for general public (contact: JF Cadorin, jf.cadorin@ulg.ac.be or JM Franssen, jm.franssen@ulg.ac.be).

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7 A COMPARISON BETWEEN THE PARAMETRIC FIRE OF EUROCODE 1 AND EXPERIMENTAL TESTS

7.1 INTRODUCTION

Nominal fire curves, such as those presented in ISO 834 [1] or ASTM E119 [2], are time temperature relationships which are very useful when used in a grading system, either by experimental testing or by calculation, but they may be a very poor representation of a real fire which could develop in a particular building. They are thus of very little help to assess the behaviour of, say, a critical structural element in a particular building.

Parametric fires provide a simple mean to take into account the most important physical phenomenon which may influence the development of a fire in a particular building. Like nominal fires, they consist of time temperature relationships, but these relationships contain some parameters deemed to represent particular aspects of the reality. In almost every parametric fire which can be found in the literature, three parameters are taken into account, in a way or another, namely

- the fire load present in the compartment,
- the openings present in the walls and/or in the roof and
- the type and nature of the different walls of the compartment.

Parametric fires are based on the hypothesis that the temperature is uniform in the compartment, which limits their field of application to post-flashover fires in compartments of moderated dimensions. They nevertheless form a significant step forward toward the consideration of the real nature of a particular fire when compared to nominal fires, while still having the simplicity of some analytical expressions, i.e. no sophisticated computer tool is required for their application.

A proposal is made in the informative annex B of Eurocode 1 – Part 2-2 [3] for such a parametric fire. The aim of this work is to compare the results provided by this proposal with the result of experimental tests, to improve this proposal if necessary and to increase its field of application if possible.

7.2 THE PARAMETRIC FIRE OF EUROCODE 1

The evolution of the gas temperature in the compartment is given by :

$$\Theta_g = 1325\left(1 - 0{,}324e^{-0{,}2t^*} - 0{,}204e^{-1{,}7t^*} - 0{,}472e^{-19t^*}\right) \tag{7.1}$$

with

$$t^* = \Gamma t \tag{7.2}$$

$$\Gamma = \frac{(O/0{,}04)^2}{(b/1160)^2} \tag{7.3}$$

$$O = A_v \sqrt{h} / A_t \tag{7.4}$$

$$b = \sqrt{c \rho \lambda} \tag{7.5}$$

and

t time, in hour,
A_v area of vertical openings, in m²,
h height of vertical openings, in m,
A_t total area of enclosure (walls, ceiling and floor, including openings), in m²,
c, ρ and λ thermal properties of boundary of enclosure (b in J/m²s$^{1/2}$K).

Equation 7.1 describes the evolution of the temperature during the heating phase, the duration of which is determined by the fire load according to equation 7.6.

$$\mathbf{t_d^*} = \mathbf{0{,}13 \times 10^{-3}\, q_{t,d}\, \Gamma / O} \tag{7.6}$$

with $q_{t,d}$ design value of the fire load density related to A_t, in MJ/m².

The temperature-time curve in the cooling phase is given by:

$$\Theta_g = \Theta_{max} - 625\left(t - t_d^*\right) \quad \text{for} \quad \mathbf{t_d^* \le 0{,}5} \tag{7.7}$$

$$\Theta_g = \Theta_{max} - 250\left(3 - t_d^*\right)\left(t - t_d^*\right) \quad \text{for} \quad \mathbf{0{,}5 \le t_d^* \le 2{,}0} \tag{7.8}$$

$$\Theta_g = \Theta_{max} - 250\left(t - t_d^*\right) \quad \text{for} \quad \mathbf{2{,}0 \le t_d^*} \tag{7.9}$$

with θ_{max} maximum temperature in the heating phase, for $t^* = t_d^*$.

This parametric fire is valid for compartments up to 100 m² of floor area, without openings in the roof and for a maximum compartment height of 4 m. b must be in the range 1.000 to 2.000, and O must be comprised between 0,02 and 0,20 .

Figure 7.1 shows the shape of the temperature-time curve given by equations 7.1 and 7.7. It has been drawn for an opening factor O equal to 0,04 and a thermal effusivity of the walls b equal to 1.160. For this case, the heating curve is very similar to the ISO curve. Increasing the opening factor would lead to a shorter but more severe fire. The fire load is 150 MJ/m², leading to a fire duration of 30 minutes. Modifying the fire load has an influence on the duration of the heating phase.

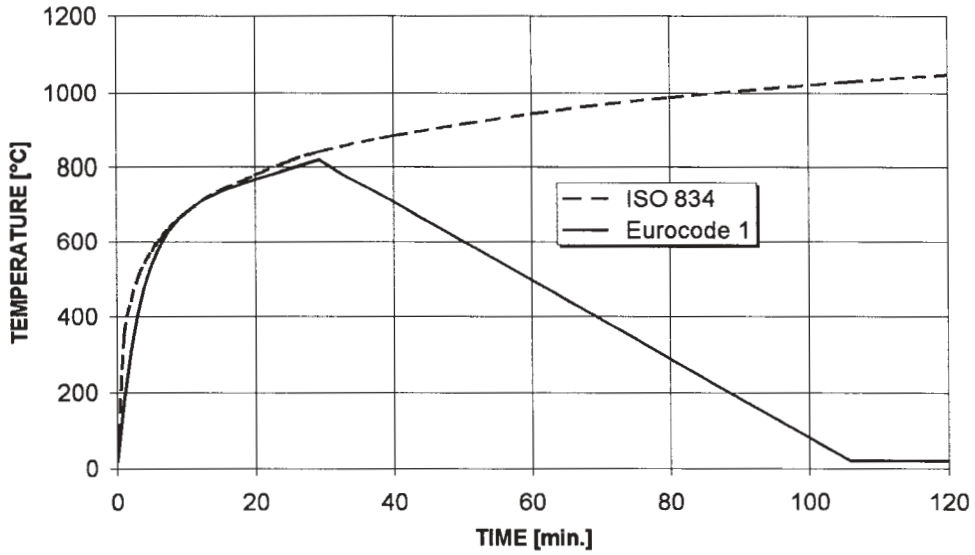


Figure 7.1 : parametric fire and ISO curve

7.3 COMPARISON OF ANNEX B OF EC1 WITH EXPERIMENTAL RESULTS

The results provided by the parametric fire of Eurocode 1 have been compared with gas temperature measurements made during experimental tests [4]. This data base comprises 48 experimental tests. The opening factor O varies from 0,055 to 0,157. The fire load $q_{t,d}$ varies from 38 to 151 MJ/m². Strictly speaking, the b factor is out of the range of application of the annex B of EC1 because the enclosure is made of light weight materials. The b factor is nevertheless very close to the limit of 1000 for 75 % of the tests, see Table 7.1, and has a value at least equal to 75% of the limit for the other 12 tests.

Value of b	Number of tests
751	9
833	3
958	24
996	12

Table 7.1 : thermal effusivity of the enclosure in the tests

On Figure 7.2, each test is represented by one point obtained from the maximum temperature in the air calculated by the Eurocode proposal (vertical axis) and measured in the test (horizontal axis). For the tests, the temperature is the average value of several measurement made by different thermocouples located in the compartment. The full line on this figure represents the place where all the points should be located if the prediction was perfect. The doted line represents a linear regression of the points.

It appears that, with the test series considered here, there is virtually no correlation between the measured maximum temperature and the maximum temperature predicted by the parametric fire of Eurocode 1. The coefficient of correlation between the experimental results and the calculated results is only 0,19.

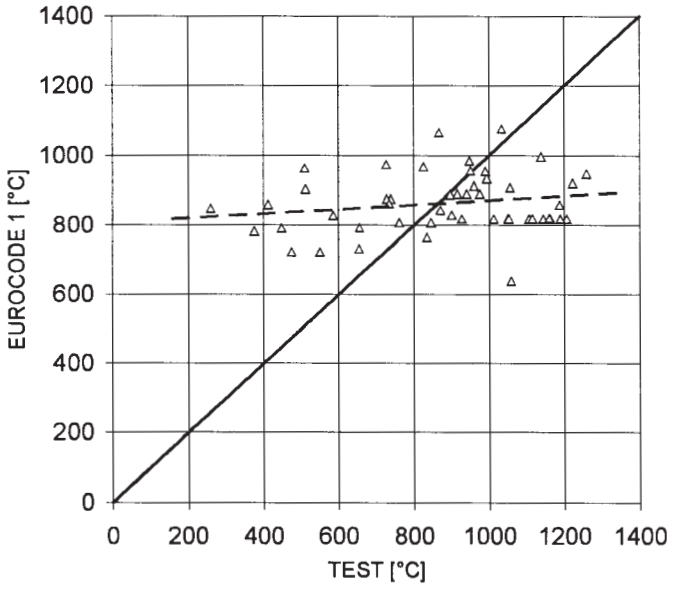


Figure 7.2 : maximum temperature in the air

The maximum temperature is only a scalar and it can be questioned whether it correctly represents the whole fire development. It could happen that an otherwise totally bad prediction appears to have the correct maximum temperature and would therefore lead to a point which would be correctly located on Figure 7.1. In order to address this point, it was decided for each fire to compute the temperature development in an unprotected steel profile having a massivity factor of 157 m^{-1}, a UB 457 x 152 x 74, for example. The steel temperature has been calculated, first with the air temperature given by the Eurocode parametric fire as an input, then with the air temperature measured in the test as an input. Thermal properties were those of Eurocode 3 [5]. The maximum temperature in the steel profile allows some kind of time integration of the evolution of the air temperature. Also, it is the key parameter when it comes to structural integrity of the structure. Figure 7.3 shows the results obtained for the temperature in the unprotected steel profile.

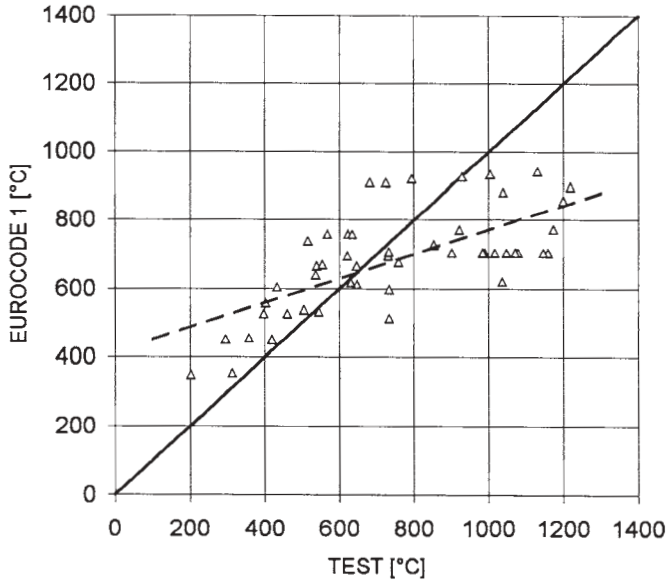


Figure 7.3 : maximum temperature in the unprotected steel profile

There seems now to be some degree of correlation between the tests and the parametric fire. The higher the temperatures calculated from the experimental measurements, the higher the temperatures calculated from the parametric fire. The correlation is still rather weak, with a coefficient of correlation of 0,66.

In fact, a more detailed examination of the curves showing the evolution of the temperature in the air and the evolution of the temperature in the steel section shows that the curve of the steel temperature generally has a shape very similar to the shape of the air temperature. The steel curve is just lagging some minutes and/or some degrees behind the gas curve. Therefore, the maximum temperature in the steel section gives the same kind of indication as the maximum temperature in the air concerning the quality of the prediction. In other words, Figure 7.3 could not give a result significantly different from Figure 7.2.

The temperature in a thermally protected profile, on the other hand, is more influenced by the duration of the thermal solicitation, here the fire, than by the severity of the fire. Therefore, the evolution of the temperature in the same steel section was computed again, with the input coming from the measurement and then from the parametric fire, but this time with a 2 cm layer of thermal insulation, this material having a thermal conductivity λ of 0,20 and a specific heat c_ρ equal to 0,555 MJ/m³K. The results of this comparison are presented on Figure 7.4.

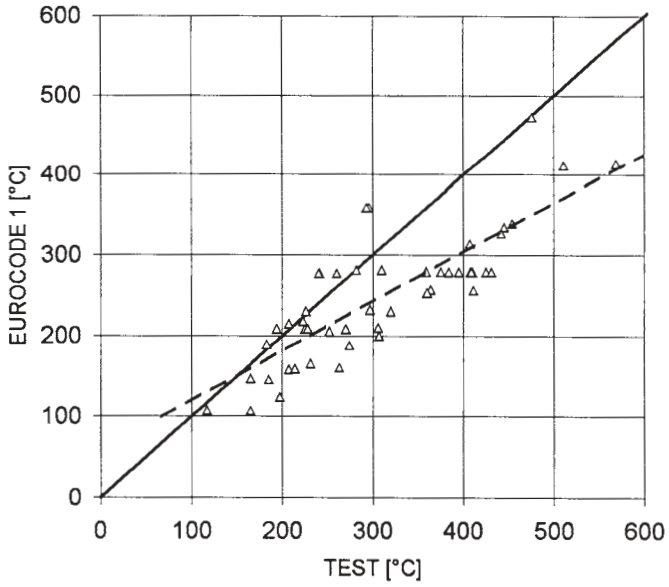


Figure 7.4 : maximum temperature in the protected steel profile

The correlation appears now somewhat better, with a coefficient of correlation equal to 0,80. The Eurocode parametric fire nevertheless leads to temperatures which are almost systematically lower than those produced by the experimental air temperatures, thus leading to an unsafe estimation of the fire resistance time.

7.4 MEANS OF IMPROVEMENT

Properties of the walls

In quite a great number of tests from the data base, the walls are made of several layers of different materials. For example, a brick wall insulated by a layer of mineral wool. For these situations, Eurocode 1 gives an alternative to equation 7.5 to calculate the equivalent thermal effusivity of the wall, b_{eq} . If, in a 2 layers wall, we give the number 1 to the fire exposed side, then the equation of Eurocode 1 is:

$$b_{eq} = \sqrt{\frac{s_1 c_1 \lambda_1 + s_2 c_2 \lambda_2}{\frac{s_1 c_1 \lambda_1}{b_1^2} + \frac{s_2 c_2 \lambda_2}{b_2^2}}} \qquad (7.10)$$

with s_1 thickness of layer 1.

There are two major problems with equation 7.10.

- The first one is that this equation is symmetric in 1 and 2. In other words, a wall made of a heavy material insulated from the fire by a lightweight material has the same b_{eq} as a wall with a core made of the lightweight material covered by a layer of the heavy material. It is clear that, in reality, the energy transferred from the hot air to the wall will be mainly influenced by the material which is in direct contact with the air.

- The second one is that the thickness of each layer plays the same role. Due to this, a wall made of a reasonable thickness of a material 1 covering a very thick material 2 will have an equivalent effusivity almost equal to b_2 whereas, in reality, this material 2 will play a secondary role.

In order to analyse this effect and make a new proposal leading to a better estimation of the equivalent b factor, several two layers walls have been analysed with the numerical code SAFIR developed at the University of Liege. Each wall was submitted to the ISO fire and the amount of energy absorbed by the wall was computed. This result was supposed to represent the exact solution. For each case, it was then possible to calculate the material properties of an equivalent wall made of only one material which would absorb the same amount of energy and, therefore, to identify the exact equivalent effusivity b_{eq} of the two layers wall. Two different situations emerged from the analyses :

- If a heavy material is insulated by a lightweight material, it is proposed to calculate the equivalent effusivity as the effusivity of the lightweight material, according to equation 7.11.

  $$\text{If} \quad b_1 < b_2, \qquad b_{eq} = b_1 \tag{7.11}$$

  Figure 7.5 shows the energy absorbed by the wall after 30 minutes of fire for a normal weight concrete wall insulated by a layer of mineral wool, calculated for different thickness of the mineral wool. It shows how the Eurocode 1 formula overestimates the absorbed energy due to the fact that it gives an overwhelming importance to the concrete whereas, in reality, this material is hidden by the mineral wool. The new proposal given in equation 7.11 systematically underestimates the absorbed energy and is, therefore, on the safe side. It can be seen that, as soon as a reasonable amount of insulating cover is provided, which should always be the case in practice, the assumption is also reasonably good.

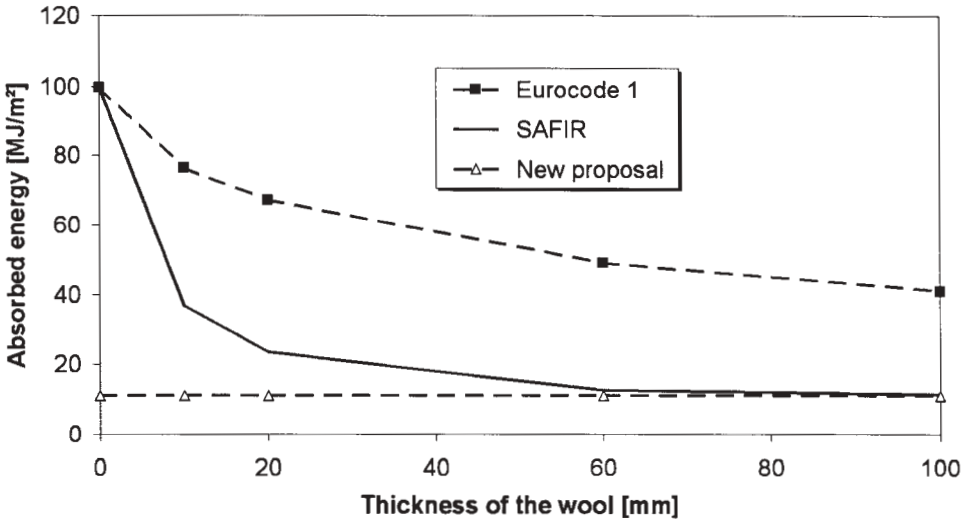


Figure 7.5 : insulating material in contact with the fire

- If a light weight material is covered by a layer of heavier material, like in a sandwich panel, for example, it is proposed to use the following procedure to calculate the equivalent effusivity of the wall.

  If $b_1 > b_2$,

  a limit thickness $s_{lim,1}$ is first calculated for the exposed material according to

$$s_{\lim,1} = \sqrt{\frac{t\lambda_1}{c_1\rho_1}} \tag{7.12}$$

  with t the time of the heating phase of the fire, in seconds.

$$\text{If} \quad s_1 > s_{\lim,1} \quad \text{then} \quad b_{eq} = b_1 \tag{7.13}$$

$$\text{If} \quad s_1 < s_{\lim,1} \quad \text{then} \quad b_{eq} = \frac{s_1}{s_{\lim,1}} b_1 + \left(1 - \frac{s_1}{s_{\lim,1}}\right) b_2 \tag{7.14}$$

  Figure 7.6 is drawn for a case which is perhaps academic but has been chosen because it is very illustrative. This is a wall made of lightweight concrete covered, on the inside face, by a layer of normal weight concrete (N.W.C. on the figure). The figure shows that the Eurocode formula almost totally neglects the contribution of the N.W.C. whereas the exact SAFIR calculation shows that it is by far not negligible. The new proposal allows to calculate a limit thickness of the first layer equal to 60 mm. The influence of the first material increases with its thickness, up to the limit thickness when the influence of the second material is totally disregarded, because it has become negligible. The second material is totally hidden by the first one.

  Other comparisons on more practical cases have shown that, for an insulating sandwich panel with steel sheets, the underestimation made by the Eurocode formula is not as severe as the one shown on Figure 7.6, but the proposed new formula is nevertheless better, leading to results almost equivalent to the exact calculations. For a gypsum board panel with mineral wool inside, The Eurocode 1 formula amounts to almost totally neglect the contribution of the gypsum board, whereas the results provided by the new proposed formula are very close to the exact solution.

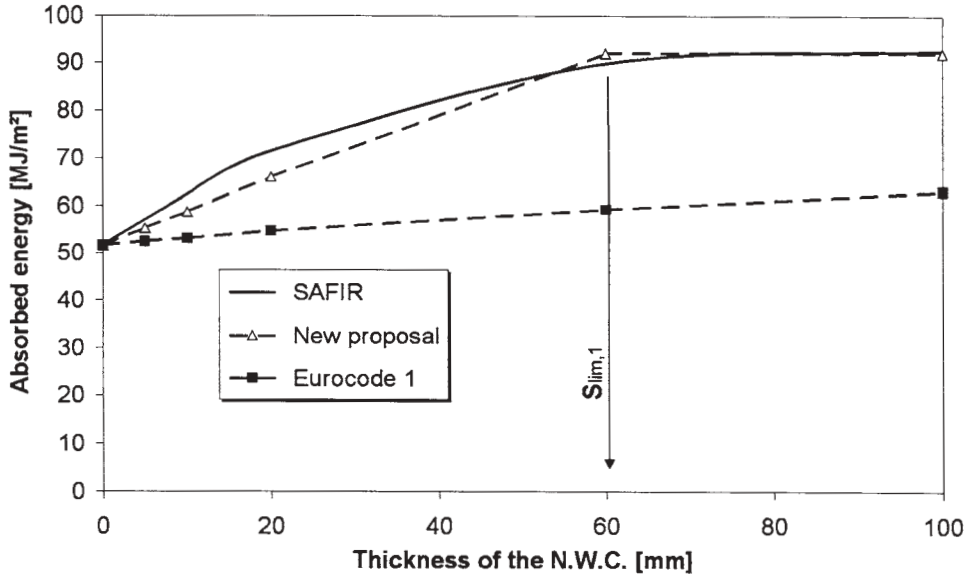


Figure 7.6 : heavy material in contact with the fire

Fuel controlled fire

One of the main hypotheses on which the parametric fire of Eurocode 1 is based is that the energy release during the fire is directly related to the opening factor. In other words, the fire is air controlled. Indeed, considering that the heat content of the fuel is 16 MJ/kg and that 70 % of the fuel load has been burnt at the end of the heating phase, Equation 7.6 can easily be transformed into the following one :

$$R = 337 A_v \sqrt{h} \tag{7.15}$$

where R is the burning rate in kg/h.

Equation 7.15 is the typical equation often quoted as Kawagoe's equation for the burning rate in an air controlled fire.
When the ratio between the fire load and the opening factor is very small, Equation 7.6 leads to very short fire duration. Our proposal is to modify Equation 7.6 and replace it by equation 7.16.

$$\mathbf{t_d = max\left(0{,}13\times10^{-3}\, q_{t,d}/O\,;\, t_{lim}\right)} \tag{7.16}$$

with t_{lim} chosen as 20 minutes, i.e. 0,33 hour, in this paper.

When applying equation 7.16, two different possibilities exist :

- Either the duration of the heating phase of the fire calculated from the first term of the equation , $\mathbf{0{,}13\times10^{-3}\, q_{t,d}/O}$, is larger than the chosen limit time $t_{lim,}$ in which case equations 7.1 to 7.4 and equations 7.7 to 7.9 are applied as such, without any modification.

- Or the duration of the heating phase of the fire calculated from the first term of the equation, $0{,}13\times10^{-3}\, q_{t,d}/O$, is shorter than the chosen limit time t_{lim}. In this case, equations 7.1 to 7.4 are applied with a modified opening factor, O_{lim}, calculated as the one leading to the chosen limit time from the following equation:

$$O_{lim} = 0{,}13\times10^{-3}\, q_{t,d}/t_{lim} \qquad (7.17)$$

Equations 7.2 and 7.3 are modified in the following way:

$$t^*_{lim} = \Gamma_{lim}\, t \qquad t^*_{lim} \text{ is used in equation 7.1 instead of } t^* \qquad (7.18)$$

$$\Gamma_{lim} = \frac{(O_{lim}/0{,}04)^2}{(b/1160)^2} \qquad (7.19)$$

Applying equation 7.1 up to the limit time t_{lim} allows to calculate the maximum temperature of the heating phase. Equations 7.7 to 7.9 which give the temperature evolution during the cooling phase are not modified, i.e. that t^* is used in these equations, and not t^*_{lim}. This is because the venting and cooling of the compartment when the fire has stopped has nothing to do with the fact that the fire was air controlled or fuel controlled during the heating phase.

Ventilation during the heating phase

The limit opening factor that has been introduced in the above paragraph allows to slow down the fire in case of large openings, because not all the air entering through the openings is used for combustion. This modification slows down the fire and reduces the temperature level. There is yet an influence of the openings which is still present when the fire is fuel controlled; the amount of gas passing through the openings is higher than what the fictitious opening factor O_{lim} tends to indicate. The mass exchange between the compartment and the exterior is higher with large openings than with small openings. A more important part of the energy produced by the fire is therefore evacuated outside by mass transfer, and this also tends to limit the elevation of the temperature in the compartment.

In order to take this effect into account, the following modification is proposed when the duration of the heating phase of the fire calculated from the first term of equation 7.16, $0{,}13\times10^{-3}\, q_{t,d}/O$, is shorter than the chosen limit time t_{lim}.

If $O > 0{,}04$ **and** $q_{t,d} < 75$ **and** $b < 1160$

$$\textbf{then}\quad k = 1 + \left(\frac{O - 0{,}04}{0{,}04}\right)\left(\frac{q_{t,d} - 75}{75}\right)\left(\frac{1160 - b}{1160}\right) \qquad (7.20)$$

$$\textbf{and}\quad \Gamma_{lim} = k\,\frac{(O_{lim}/0{,}04)^2}{(b/1160)^2} \qquad (7.21)$$

Although this modification is based on a physical phenomena, it has to be recognised that the shape and the coefficients of equation 7.20 have been derived more from a curve fitting exercise with the results of the data base than from theoretical considerations.

7.5 COMPARISON OF THE MODIFIED PARAMETRIC FIRE WITH EXPERIMENTAL RESULTS

If the parametric fire of Eurocode 1 is modified according to the proposals presented in the preceding section, the comparison can be made between the results of experimental tests and the results of the (hopefully) improved prediction. Figure 7.7 concerns the maximum temperature in the gas and has to be compared to Figure 7.2. The coefficient of correlation, which had the value of 0,19 with the Eurocode fire, has now a value of 0,83.

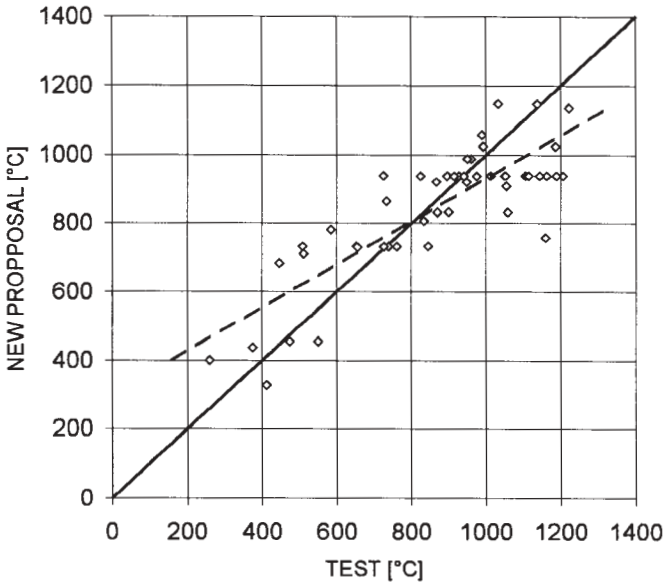


Figure 7.7 : maximum temperature in the air

Figure 7.8 has been drawn from the calculated temperatures in the unprotected steel section and has to be compared to Figure 7.3. The coefficient of correlation has been improved from 0,66 for the original Eurocode proposal to 0,76 for this new proposal.

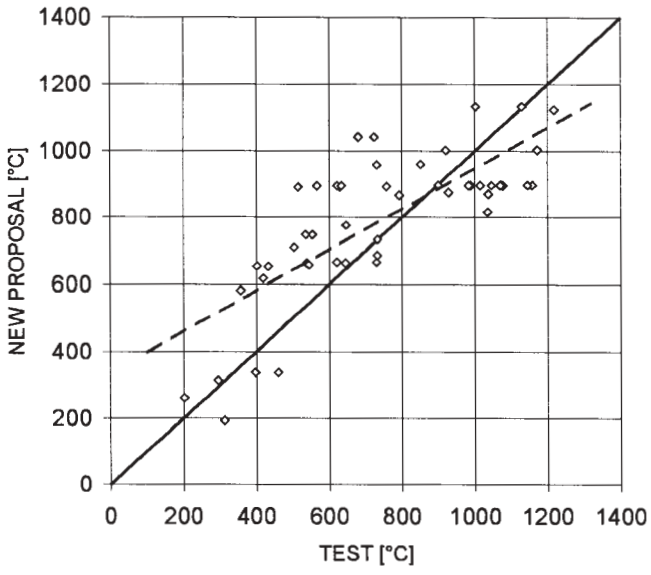


Figure 7.8 : maximum temperature in the unprotected steel profile

The comparison on the temperature of the protected steel profile is presented in Figure 7.9, to be compared with Figure 7.4. The coefficient of correlation is only marginally improved, from 0,80 to 0,81 but, more important, the results are not any more systematically on the unsafe side, see Figure 7.4, but rather on the safe side.

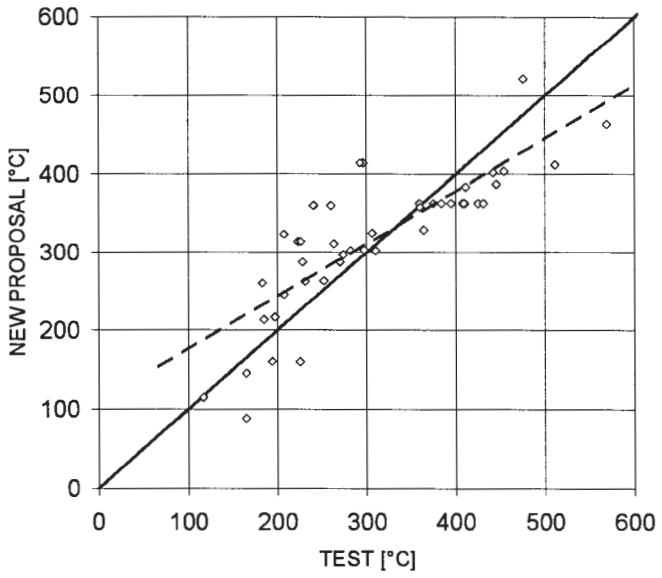


Figure 7.9 : maximum temperature in the protected steel profile

7.6 CONCLUSIONS

The maximum temperature in the compartment predicted by the parametric fire proposed in Annex B of Eurocode 1 does not correlate at all with the maximum temperature recorded in experimental tests. There is a weak correlation when the maximum temperature in an unprotected steel profile is considered and a better correlation when the temperature in a protected steel profile is considered. In this case, however, the predicted temperature is almost systematically lower than the recorded temperature.

A new proposal has been made to improve the situation. It is based on the same analytical expressions as the original Eurocode proposal but introduces some modifications for the consideration of multi layers walls and for fuel controlled fires. With this new proposal, the correlation between the calculation and the measurements is significantly improved and the results are more on the safe side.

Work is still under way on this subject because more experimental test results which have been collected have still to be introduced in the data base and taken into account.

An improved new proposal could be made in the near future if it proves to enhance the prediction even more.

7.7 REFERENCES

[1] Fire Resistance Tests - Elements of Building Construction. International Standard 834, ISO, 1975.

[2] Standard Methods of the Fire Tests of Building Construction and Materials, Designation E119-95a, ASTM, Philadelphia, 436-456, 1995.

[3] Eurocode 1 - Basis of design and actions on structures - Part 2-2: Actions on structures - Actions on structures exposed to fire. ENV 1991-2-2, CEN, Brussels, Fébr. 1995.

[4] Database

[5] Eurocode 3 : Design of steel structures. Part 1.2 : General rules. Structural fire design. Draft ENV 1993-1-2, CEN, Brussels, may 1995

8 CHOICE OF THE NATURAL FIRE MODEL : PRACTICAL GUIDELINES

8.1 INTRODUCTION

The aim of this chapter consists on defining criteria for the choice of the natural fire model to apply according to the scenario of the situation in the buildings. The natural fire concept is an alternative of the nominal fires defined in prescriptive codes. Thus, the nominal fires will not be given in this chapter.

The choice will be mainly focussed on adaptive and simple engineering tools as zone models. Indeed, the field models or CFD are too complex and need too much time and data in order to use them as a simple engineering tool. It is considered that CFD are used for very specific case, for which, for example, the geometry is very complex and has to be simulated without large simplifications. Moreover, CFD are not well adapted to fully developed fire simulations.

So the choice will be done mainly between one-zone models and two zones models.

8.2 CHOICE OF THE ZONE MODEL

Considering the fire characteristics - ie RHR curve, compartment geometry, walls characteristics, scenarios.. - are given by the WG3, the choice of the model will be made according the application domain of the models.

In this consideration, it is assumed that the first application has to be a 'two zone model' simulation. In fact, the early stage of a fire is conformed to a 'two zone model' application. The question is relative to how and when appears the transition from the 'two zone model' application to a 'one zone model application'.

According to the results of this simulation for given fire characteristics, the use of 'one-zone models' is prescribed or not.

The results of a 'two-zone model' are given in form of two main variables:

- temperature of the upper zone T_u
- height of the interface of the two zones H_i

These two variables will condition the simulation with the zone model. The four following conditions are able to limit the application of a 'two zone model' :

- condition 1 (C1) : $T_u > 500°C$
  The high temperature of combustion products (higher than 500°C) leads to a flashover by radiative flux to the other fire loads of the compartment.

- condition 2 (C2) : $H_i < H_q$ and $T_u > T_{ignition}$
  The decrease of the interface height (H_i) leads to put combustible in the smoke layer (maximum height with combustible H_q), and if the smoke layer has a high temperature (higher than $T_{ignition}$ which is assumed be 300°C), leads to propagation of fire in all compartment by combustible ignition.
- condition 3 (C3) : $H_i < 0,1\ H$
  The interface height goes down and leads to a very small lower layer thickness, which is not representative of two zone phenomenon
- condition 4 (C4) : $A_{fi} > 0,5\ A_f$
  The fire area is too high compared to the floor surface of the compartment to consider a localised fire.

In fact, the conditions 1 or 2 leads to a modification of the initial rate of heat release (simulation with two zone model), for a one-zone model simulation. This modification is made as Figure 8.1 indication.

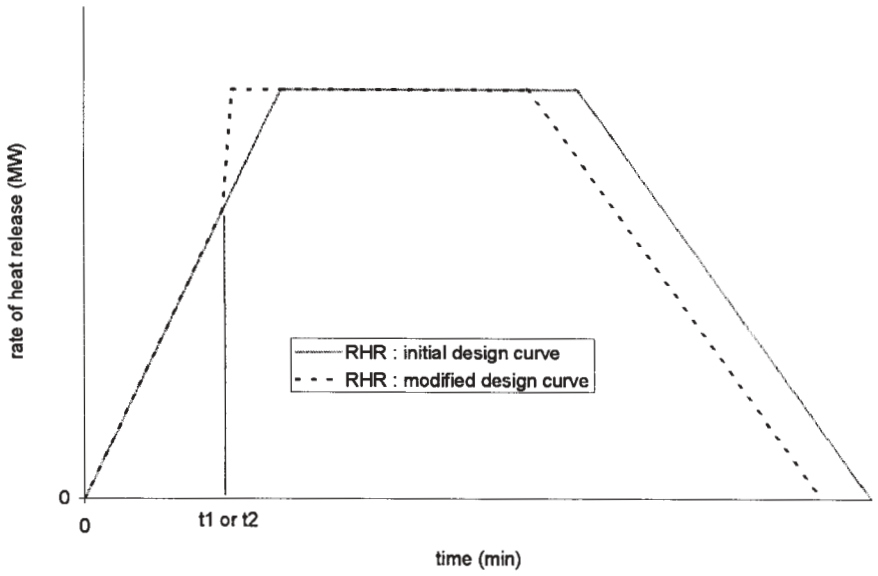


Figure 8.1 : design curves for rate of heat release of the fire

According to these conditions, it can be considered two fire load assumptions : localised fire loads or distribution of fire loads on all compartment floor.

8.2.1 Localised fire loads

In case of localised fire loads, the condition 4 can not occur. The fire load area is limited.

The conditions 1 and 2 leads to a modification of the rate of heat release of the fire considering that all fire loads are ignited. So considering the surface $A_{fi,j}$ of the localised fire load j, when condition 1 or 2 occurs, the fire surface becomes : $\sum_j A_{fi,j}$.

It means that the fire is defined by several localised fires.

Nevertheless, the fire is always localised, and the two-zone model is always adapted to the fire simulation.

If the condition 3 occurs, the fire simulation has to be done by a 'one zone model'. The fire source and the fire growth are not modified. In such case, two simulations are made, in one hand, the two zone simulations up to the time t_3 when the condition 3 occurs (Figure 8.2a), and the one zone simulation from the beginning of the fire to the fire extinction (Figure 8.2b). From these simulations, the design curve used for thermal actions to structural elements is defined by the Figure 8.2c. This design curve is defined by the 'two zone' simulation up to t_3, a temperature plateau to reach the 'one zone' curve, and the 'one zone curve'. In the condition 3, the small value of the interface height leads to a small difference between the 'one zone' temperature and upper layer temperature of the two zone simulation.

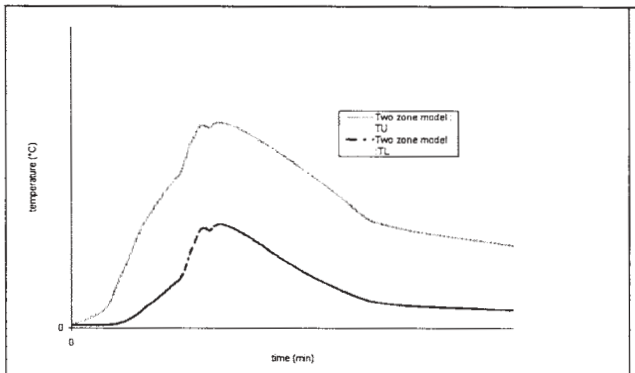


Figure 8.2a : Two zone simulation

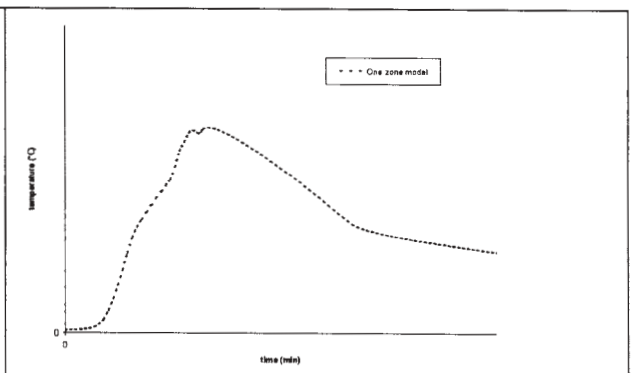


Figure 8.2b : One zone simulation

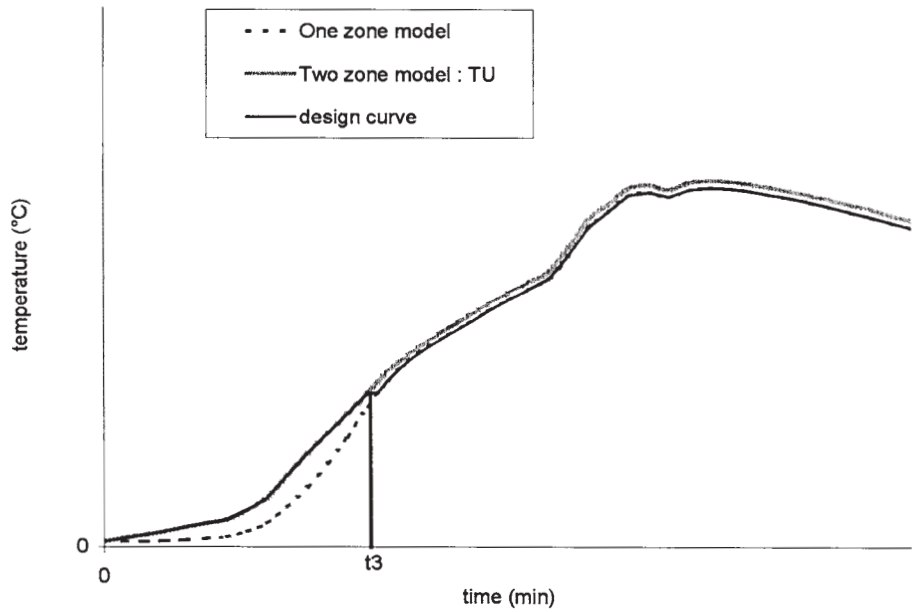


Figure 8.2c

8.2.2 Uniformly distributed fire loads

Occurrence of conditions 1 or 2 :

In the occurrence of condition 1 (time t1) or 2 (time t_2) in the two zone simulation, a flashover or a quicker propagation of fire happens. In such case, a one zone simulation has to be made with a modified rate of heat release design curve, considering a quick increase of rate of heat release at the time t_1 or t_2 such as the fire load area goes up to floor area.

In occurrence of condition 1 or 2, the design temperature-time curve resulting from two zone simulation (Figure 8.3a) and one zone simulation (Figure 8.3b) can be deduced according to the Figure 8.3c if the maximum temperature of the 'one zone' simulation is higher than 500°C in condition 1 or $t_{ignition}$ for condition 2.

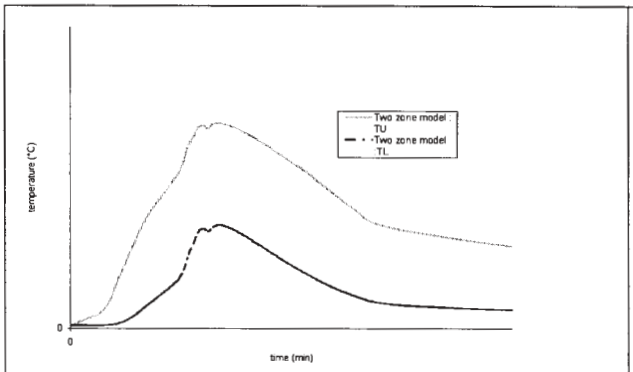


Figure 8.3a : Two zone simulation

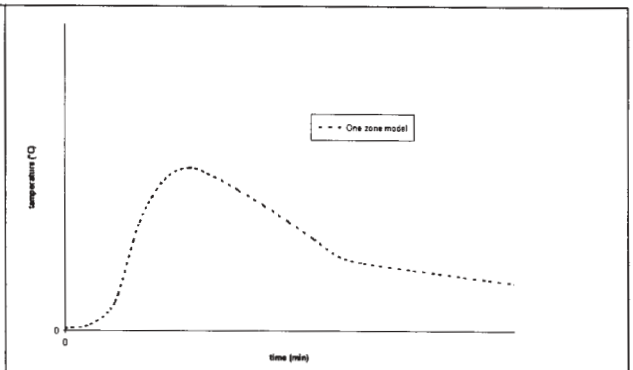


Figure 8.3b : One zone simulation

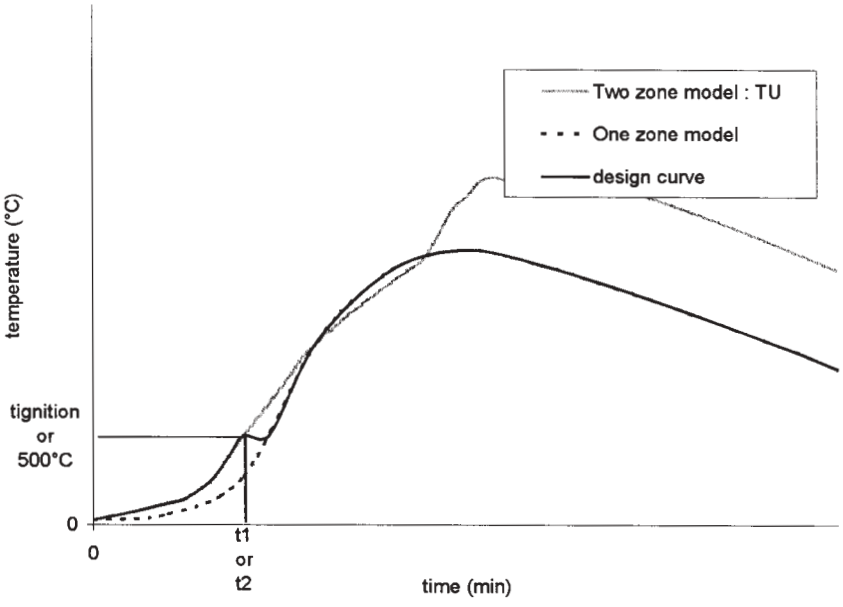


Figure 8.3c : design curve in condition 1 and 2

In the case of condition 1 or 2 occurrence, if the maximum temperature of the one zone simulation does not reach 500°C (condition 1) or $t_{ignition}$ (condition2), then the design curve is given by the Figure 8.4c, deduced from Figure 8.4a and 8.4b.

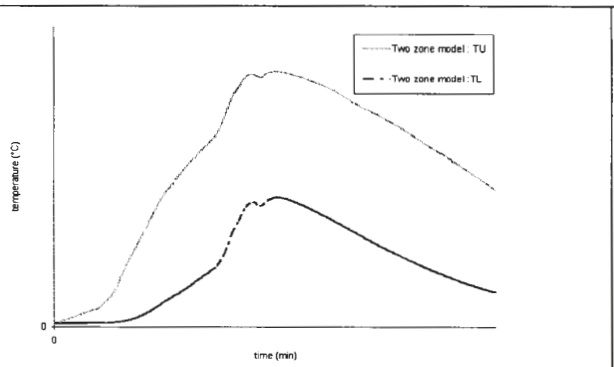


Figure 8.4a : Two zone simulation

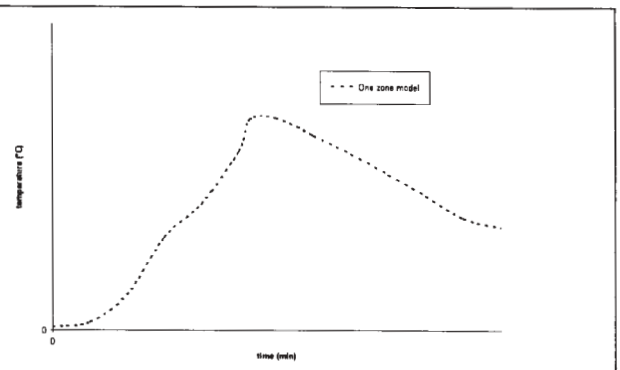


Figure 8.4b : One zone simulation

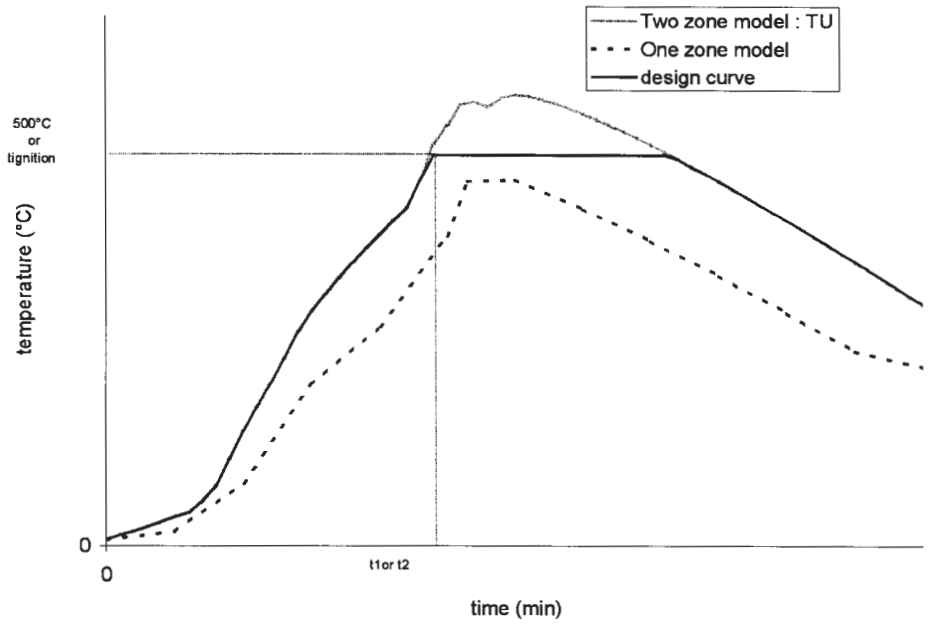


Figure 8.4c : design curve in condition 1 and 2

Occurrence of conditions 3 or 4

If conditions 3 or 4 occur during the two zone simulation, the one zone simulation has to be done considering an unmodified rate of heat release curve. According to that, the design curve defined by the Figure 8.2c can be used.

8.3 SUMMARY OF DESIGN CURVE

The following scheme (Figure 8.5) presents the way to determine the design temperature-time curve used for thermal action to structural behaviour.

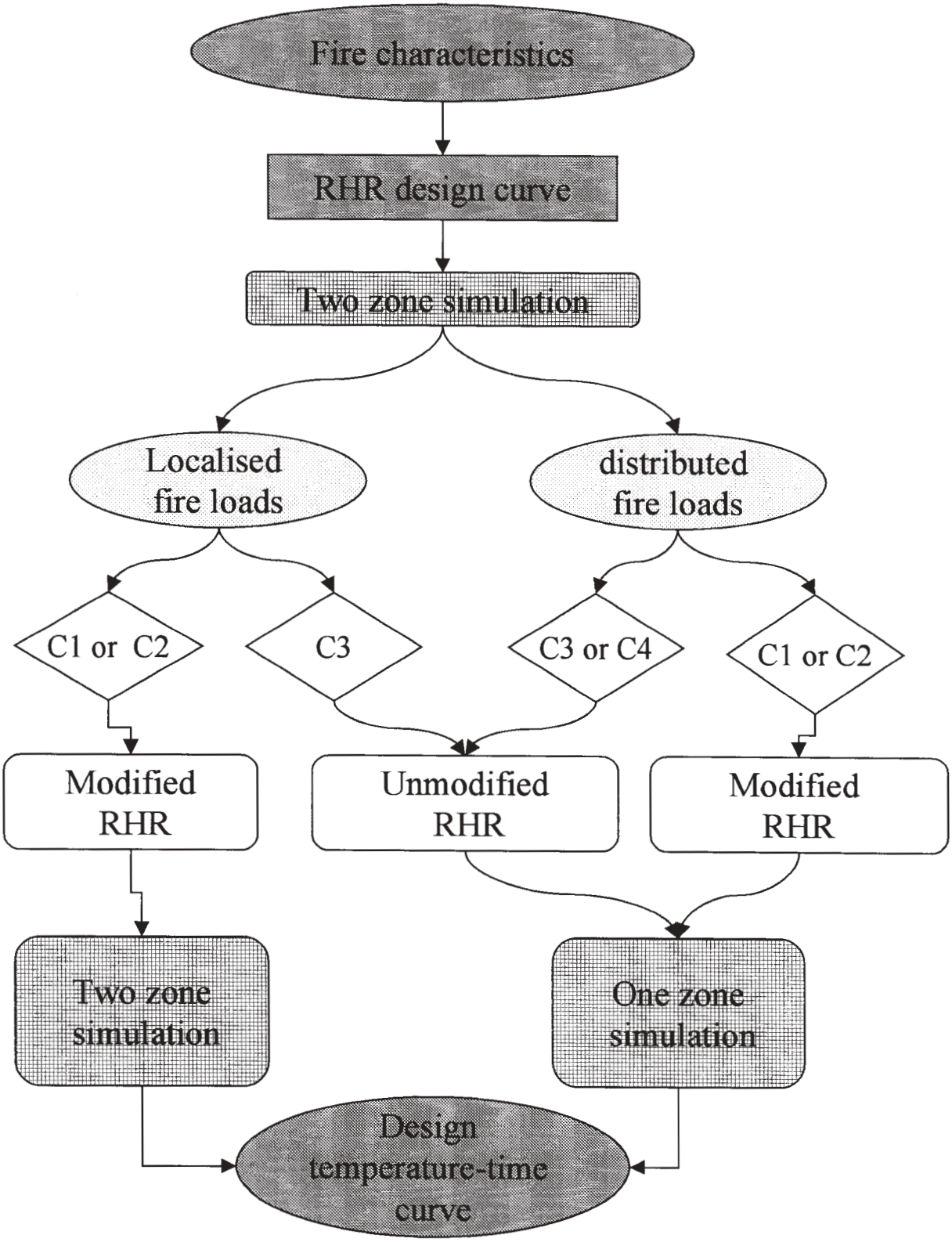


Figure 8.5 : Determination of the design temperature-time curve

ANNEXES

Annex 1: Connection between Parametric temperature-time curves and Equivalent time of fire exposure (Annexes B and E of ENV1991-2-2).

Annex 2: Comparison of Equivalent Times from Eurocode 1 part 2.2 annex E and Experimental Tests.

Annex 3: User Guides.

ANNEX 1: ACCIDENTAL ACTIONS : FIRE. CONNECTION BETWEEN PARAMETRIC TEMPERATURE-TIME CURVES AND EQUIVALENT TIME OF FIRE EXPOSURE (ANNEXES B AND E OF ENV 1991-2-2).

SUMMARY

The concept of parametric temperature-time curves presented in Annex B of Eurocode 1 : part 2-2 [1] and the concept of equivalent time of fire exposure presented in Annex E of the same document are briefly described. A nomogram is presented as a graphic help for the application of each method. Starting from a reference compartment, some parameters are modified and the two methods are applied. Via the calculation of maximum temperatures in 3 structures, it is possible to compare the two methods with regard to their severity.

A1.1 INTRODUCTION

Beyond the application of the nominal ISO temperature-time curve, Eurocode 1 proposes 2 different methods which consider more realistically the influence of some parameters on the severity of the fire such as the fire load, the geometry of the compartment and the nature of the surrounding walls. One method, proposed in Annex B, leads to parametric temperature-time curves for the air in the compartment and the other one, proposed in Annex E, leads to an equivalent time of exposure to the ISO fire supposed to have the same severity as a real fire in the compartment.

For practical situations, the designer or the authority will face the choice between one of the two methods and no indication is given in [1] concerning the correlation between them, except some limitations for the applicability of the methods. For situation where both methods are applicable, will they lead to the same "severity"? If not, is one of the methods systematically more severe? How are different parameters taken into account in the methods?

To give some answers to those questions, a parametrical study has been undertaken on a reference case. Both methods have been applied under the same conditions and the severity of the fire has been defined as the maximum temperature obtained in a structure submitted either to the temperature-time curve given by Annex B, or to the ISO fire during the equivalent time given by Annex E.

A1.2 ANNEX B OF ENV 1991-2-2: NATURAL FIRE CURVE

A1.2.1 INTRODUCTION

This Annex is based on a paper of U. Wickström [1]. In case of a compartment with $O = 0{,}04 m^{1/2}$ and $b = 1.160 J/(m^2 s^{1/2} K)$, the parametric curve is almost exactly the ISO-curve. The nomogram explained hereafter has been developed to make easier the use of this Annex.

A1.2.2 NOMOGRAM OF PARAMETRIC TEMPERATURE TIME CURVES (ANNEX B OF ENV 1991-2-2)

The first step in finding the time dependent progress of temperature is to calculate the opening factor, $O[m^{1/2}]$, found on the upper x axis. This is done by solving the following definition:

$$O = \left[A_v \frac{\sqrt{h}}{A_t} \right]$$

A_V = area of vertical openings (m^2)
h = height of vertical openings (m)
A_t = total area of enclosure, walls, ceiling and floor (1) (including openings) (m^2) (A1.1)

limits being: $0{,}02 \leq O \leq 0{,}2\ [m^{1/2}]$.

This value is found on the upper x axis and a vertical line is extended downwards (1) from this point until it meets the corresponding materials value line, b.
The value of b is calculated by the equation:

$$b = \sqrt{(\rho, c, \lambda)}$$

ρ = density of enclosure [kg/m^3]
c = specific heat of enclosure (J/kgK) (A1.2)
λ = thermal conductivity of enclosure (W/mK)

To account for enclosures with different layers of material or for different materials in walls, ceiling and floor, see points 4 and 5 of Annex B ENV 1991-2-2. [2]

For this step in the procedures the equation $\Gamma = [O/b]^2 \Big/ \left(\frac{0{,}04}{1160}\right)^2$ is used. (A1.3)

From this point on the materials line a horizontal line is charted across from left to right (A1.2) to cross the time lines which emanate from the upper zero on the y axis. This line forms a new artificial time axis, the scale based upon the points where the time lines cross that artificial axis. Thus with the temperature line, the temperature path of the fire with time can be easily charted.

The original equation for the temperature against time is taken from

$$\theta_g = 1325\left(1 - 0{,}324e^{-0{,}2t^*} - 0{,}204e^{-1{,}7t^*} - 0{,}472e^{-19t^*}\right) \quad \text{(A1.4)}$$

The next step is to find the position of maximum temperature and the time that it occurs. This is done by recommencing with the initial value for the opening factor, but this time starting on the O values found on the lower portion of the y axis.

From this point a horizontal line is charted to the corresponding fire load line (A1.3) then charted vertically up to the lower x axis (A1.4). Passing through this intersection, a new line starting from the upper zero on the y axis is drawn. This line continues along this path (A1.5) until it strikes the new artificial time axis (this point being t_d). From this point a vertical line is charted up through the lower x (time) axis (this point being t_d^*) until it crosses the temperature curve (A1.6). This point is defined by the time t_d and the maximum temperature θ_{max} provided by the horizontal line 7.

For this step the equation base is defined by

$$t_d^* = \left(0{,}13 \times 10^{-3} \cdot q_{t,d} \cdot \Gamma\right)/O \text{ and } t_d^* = \Gamma \cdot t_d \quad \text{(A1.5)}$$

$$t_d = 0{,}13 \times 10^{-3} \cdot q_{t,d} / O \quad \text{(A1.6)}$$

The value of $q_{t,d}$ is the design value of the fire load density related to the surface area A_t of the enclosure

$$q_{t,d} = q_{f,d} \cdot A_f/A_t \ [MJ/m^2] \quad \text{(A1.7)}$$

$q_{f,d}$ = design value of the fire load density related to the surface area A_f of the floor $[MJ/m^2]$

At the point (t_d, θ_{max}) the linear temperature decrease will begin, this being defined by point 6 of Annex B ENV1991-2-2 as a function of t_d^*.

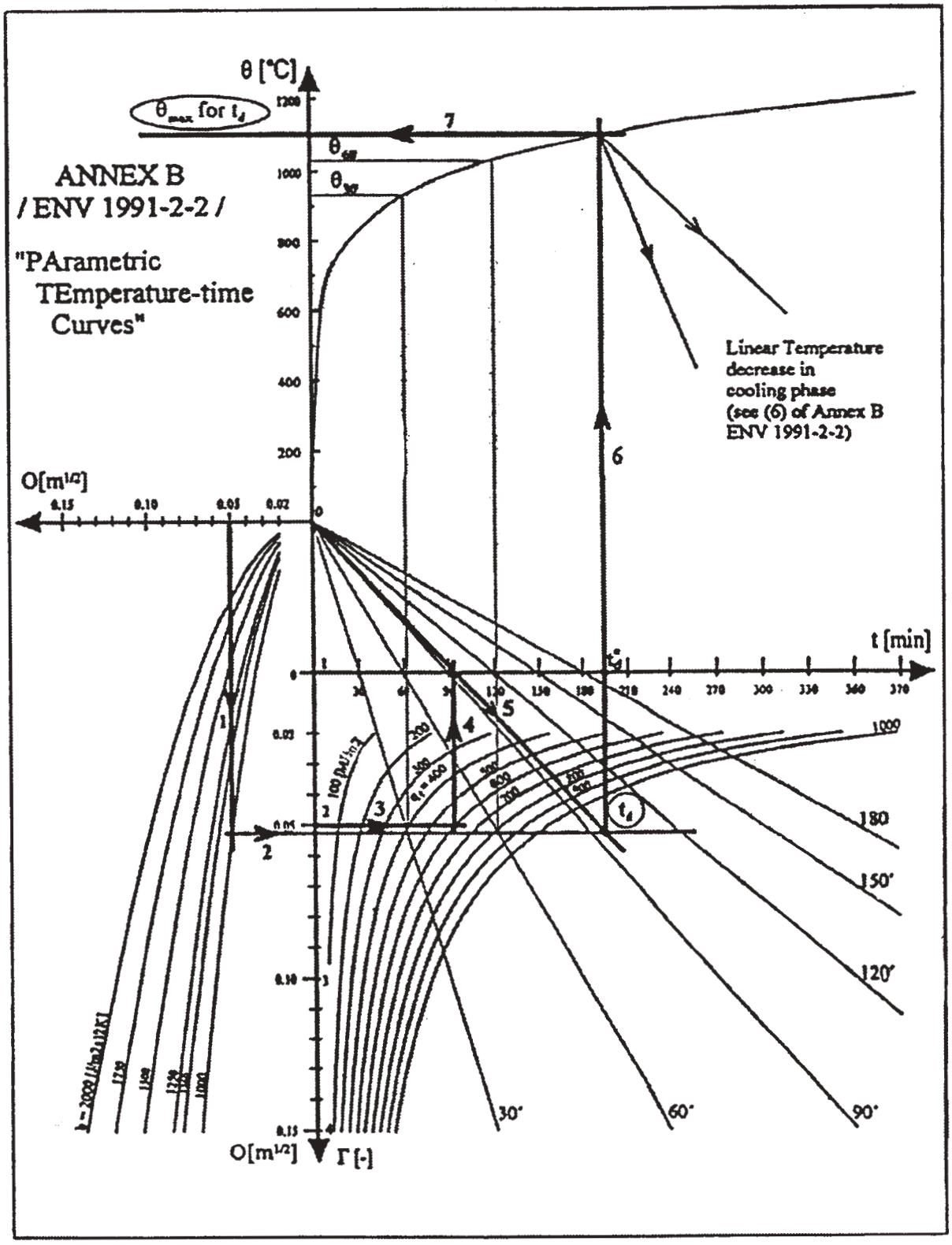


Figure A1.1 : Annex B Nomogram

A1.3 ANNEX E OF ENV 1991-2-2: EQUIVALENT TIME

A1.3.1 DESCRIPTION OF THE METHOD

Annex E of Eurocode 1 offers a simple equation (A1.8) to determine the required fire resistance time $t_{e,d}$ for a compartment, equivalent to the same duration of an ISO curve fire.

$$t_{e,d} = q_d \, k_b \, w_f \qquad \text{(A1.8)}$$

Before starting the calculation, it is necessary to determine the floor area of the compartment A_f as well as the total fire load $Q_{fi,k}$,mainly depending on the combustibility of the component parts and of the stored material. Annex D of [2] can be applied for this purpose. The design fire load density $q_{f,d}$ can be obtained from the multiplication of the characteristic fire load q_k by the safety factors γ_n and γ_q for the accepted failure risk in the case of fire and the influence of active fire measures, eq. A1.9.

$$q_d = \gamma_q \, \gamma_n \, q_k = \gamma_q \, \gamma_n \, \frac{Q_{fi,k}}{A_f} \qquad \text{(A1.9)}$$

The conversion factor k_b in equation (A1.8) accounts for the heat transfer in the neighbouring component parts of the compartment. It depends on the thermal properties of the walls and ceilings of the enclosure, see table E.1 of [2].

The ventilation factor w_f can be calculated by the following equation ;

$$\mathbf{w_f = \left(\frac{6}{H}\right)^{0,3} \left(0{,}62 + 90\,(0{,}4 - \alpha_v)^4 / (1 + b_v \alpha_h)\right) \geq 0{,}5} \qquad \text{(A1.10)}$$

This equation depends on the height of the compartment H and on the ratios of the vertical (α_v) and horizontal (α_h) opening areas to the floor area A_f.
The dimensionless factor b_v can be determined by the following equation ;

$$\mathbf{b_v = 12{,}5\left(1 + 10\alpha_v - \alpha_v^2\right) \geq 10} \qquad \text{(A1.11)}$$

In case of small compartments, $A_f < 100$ m², Annex E allows to use the more simple equation A1.12. to calculate the ventilation factor ;

$$w_f = O^{-1/2} \; A_f / A_t \qquad \text{(A1.12)}$$

with the opening factor O being calculated according to Annex B, see eq. A1.1.

A1.3.2 NOMOGRAM OF EQUIVALENT TIME METHOD (ANNEX E OF ENV 1991 2-2)

Two nomograms are presented in Figure 2. The first one (upper two drawings) can be used when there is no horizontal openings in the compartment (α_h=0). The second one (lower two drawings) is made considering that the compartment has the minimum of vertical opening (α_v=2,5%). The left drawings enable to calculate w_f (equation A1.10) in function of the dimensionless factor α_v (upper left drawing) or α_h (lower left drawing) and in function of the height of the compartment H. The right drawings enable to calculate the equivalent time in function of the w_f factor found on the left figure and in function of the design fire load density times the conversion factor k_b (equation A1.8).

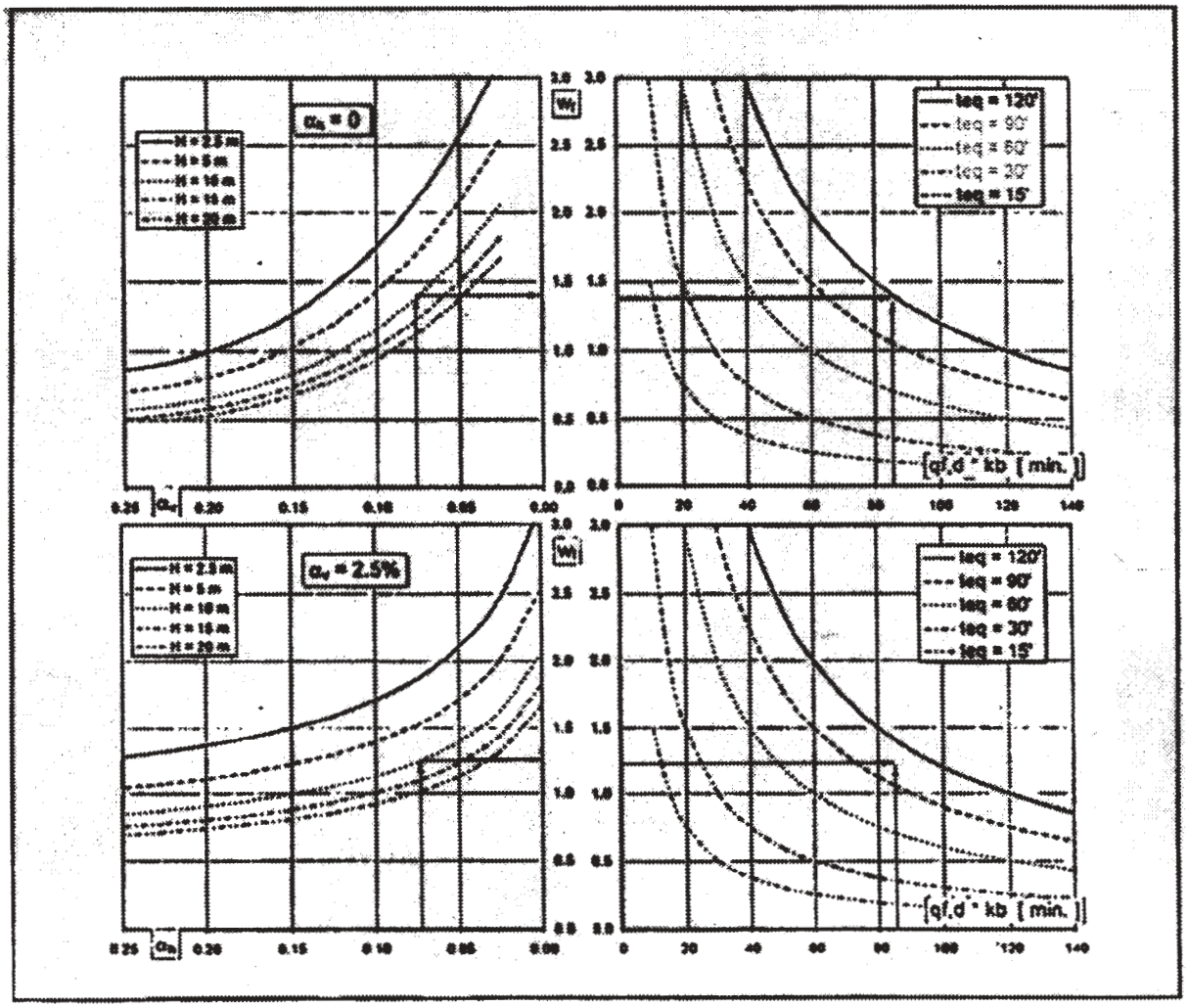


Figure A1.2: Nomogram of Equivalent time

A1.4 COMPARISON BETWEEN ANNEX B AND ANNEX E

A1.4.1 FIRST LOOK ON THE EQUATIONS OF THE 2 METHODS

It is interesting to notice that t_d^* from Annex B can be considered as an equivalent ISO time which is related to the temperature of a very light steel element (with a very big section factor, see EC3 Part 1.2). In other words, an element whose temperature is very close to the gas temperature. In Annex B, t_d^* is proportional to the opening factor O (eq A1.5 & A1.3) while in Annex E $t_{e,d}$ is proportional to $O^{-1/2}$. It will be verified by the parametrical study whether this apparent contradiction has practical effects.

4.2 Parametrical study

A parametrical study has been made with the 2 methods. 7 parameters are taken into account:

- the floor area of the compartment, A_f in m^2 — 16; **25**; 36; 64; 100; 144; 256; 324; 400
- the height of the compartment, H in m — 2,4; **2,5**; 3,0; 3,5; 4,0; 4,5; 5,0
- the design fire load density, q_d in MJ/m^2 — 250; 500; **750**; 1000; 1250; 1500; 1750; 2000
- the opening height, h in m — 0,2; 0,5; 1,0; **1,5**; 2,0; 2,5
- the position of the sill of the opening, h_s in m — 0,0; **0,5**; 1,0
- the width of the opening, w in m — 0,5; 1,0; 2,0; 3,0; **4,0**; 5,0
- the characteristics of the walls, b in $J/m^2s^{0,5}K$ — 500; 1000; **1300**; 1600; 2000

The bold values are those of the **reference case**. The variation is made separately on the parameters. While one of them is allowed to vary from the reference case, the values of the other parameters remain fixed to the values of the reference case. This leads to 38 different cases. For the reference case we have the 7 bold values of the parameters and for the 37 other cases we have 6 bold values and one non bold value.

The results of this study are in case of annex B a set of temperature-time curves and in case of annex E a set of equivalent time. Figure A1.3 shows the results obtained by the 2 methods for the variation of the parameter A_f.

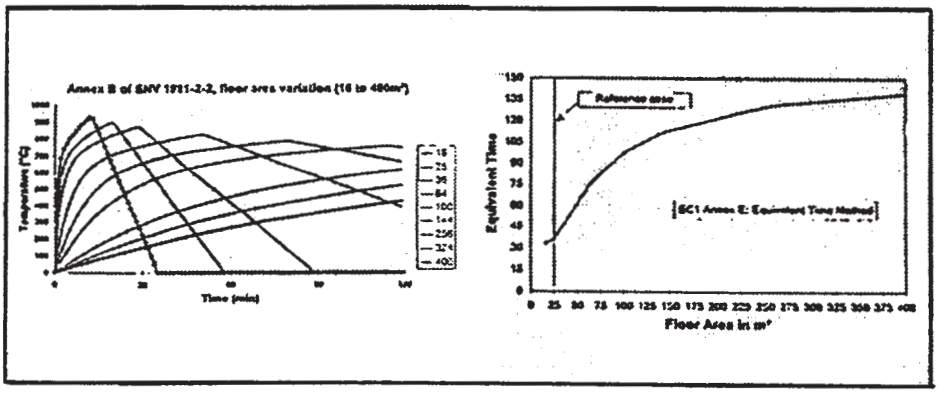


Figure A1.3: Results obtained by the 2 methods

A1.4.3 LINK BETWEEN THE TWO METHODS

In order to make a comparison between those methods we have to transform the results obtained with Annex B into equivalent times. This is done by calculations of temperatures in a structure and observation of the maximum temperature reached by this structure. Three structures have been chosen here;

- *Unprotected steel section.* In this case, the calculation of the uniform temperature is made by the method described in § 4.2.5.1. of Eurocode 3 : Part 1-2 [3]. A massivity of 211 m^{-1} was chosen corresponding, for example, to a HE 200 A section.
- *Protected steel section.* The same massivity is taken as for the unprotected section. The lightweight insulating material has the following properties: c_P = 850 J/(kgK); λ_P = 0,15 W/(m²K); ρ_P = 300 kg/m^3 ; thickness = 20 mm. Those characteristics are similar to vermiculite. Here the calculation of the uniform temperature is made by the method described in § 4.2.5.2. of Eurocode 3 : Part 1-2 [3].
- *Concrete structure.* The temperature is calculated in a semi-infinite concrete volume, at a penetration depth of 3 cm. The calculations are made with the non linear finite element code SAFIR of the University of Liège.

For the thermal calculations, steel and concrete thermal properties are taken from Eurocode 4 : part 1-2 [4].

The temperature in the structures submitted to the ISO curve is first calculated as a function of time. The same calculation is made for the same structures submitted to the natural fire curves obtained from annex B. In each case, the maximum temperature obtained in a structure submitted to a parametric temperature-time curve is reported on the corresponding curve obtained by the first calculation when the structure was submitted to the ISO curve. The moment when this temperature was obtained is defined as the equivalent time.

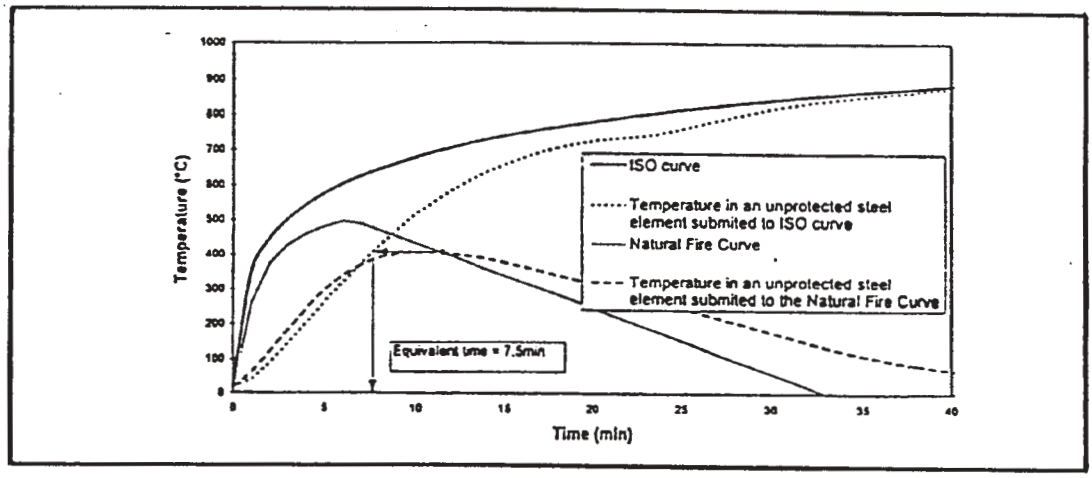


Figure A1.4: Link between Natural Fire Curve and Equivalent Time

In other words, the equivalent time is the time during which a defined structure has to be submitted to the ISO fire curve in order to obtain, in the structure, the same effect (maximum temperature) as the natural fire curve would have produced.

A1.4.4 RESULTS

The position of the sill of the opening has no influence on the results, for the Annex B method as well as for the annex E method. The 6 other results of the parametrical study are shown on the figures A1.5.a and A1.5.b. The equivalent time is given in minutes as a function of the different parameters. Dotted lines are segments linking at least one point which is out of the field of application of the method used to obtain this point. The zones which are beyond the applicability limits of the methods have been shaded in grey on the figures. It appears that the equivalent times calculated with a concrete structure and with a protected steel structure are very close to each other.

This is because those two structures have the same thermal behaviour, i.e. a delay in time between the increase of temperature in the air and the temperature increase in the structure. Whether the delay is caused by a thermal protection or by a cover of concrete does not make a difference. It is also observed that these two curves are generally very similar to the equivalent time curves given by Annex E. In some cases, the variation of the equivalent time calculated from the results of the Annex B with a parameter is different for the unprotected steel element than for the two protected elements. This is due to the fact that the maximum temperature calculated in the unprotected steel is mainly influenced by the maximum temperature in the air, whereas the maximum temperature in the protected elements is also influenced by the duration of the fire. Going from a severe but short fire to a less severe but longer one is generally favourable for a pure steel section, but it can be more critical for a protected element. The same effect also explains why the apparent contradiction between Annex B and Annex E mentioned in § 4.1. disappears when temperatures are calculated in protected elements, but not in unprotected elements.

A1.5. CONCLUSIONS

Two different methods are proposed in ENV 1991-2-2 [2] to take into account the influence of physical parameters on the severity of the fire. Those parameters are the fire load, the geometry of the compartment and the thermal properties of the surrounding material. This study shows that, despite apparent contradiction in the equations, the methods proposed in Annex B and in Annex E are coherent while evaluating the temperature in a protected steel element or in a concrete element.

When considering an unprotected steel element, these two methods have lead in some cases to very different results. None of two methods is systematically safer than the other one. If it is considered that Annex B provides a good approximation of the air temperature-time curve in the compartment, based on more refined models, thus allowing the calculation of the temperature in each structure type, whereas Annex E is an attempt to simplify the solution even further and to propose equivalent time irrespective of the structure, then this study tends to indicate that the approximation is valid in case of protected elements, but may not be valid in case of unprotected steel elements. It can be noticed that the method of Annex E gives equivalent times which in each case are higher than 30 minutes. Nevertheless 30 minutes of ISO curve heating is an upper bearing limit for an unprotected steel element.

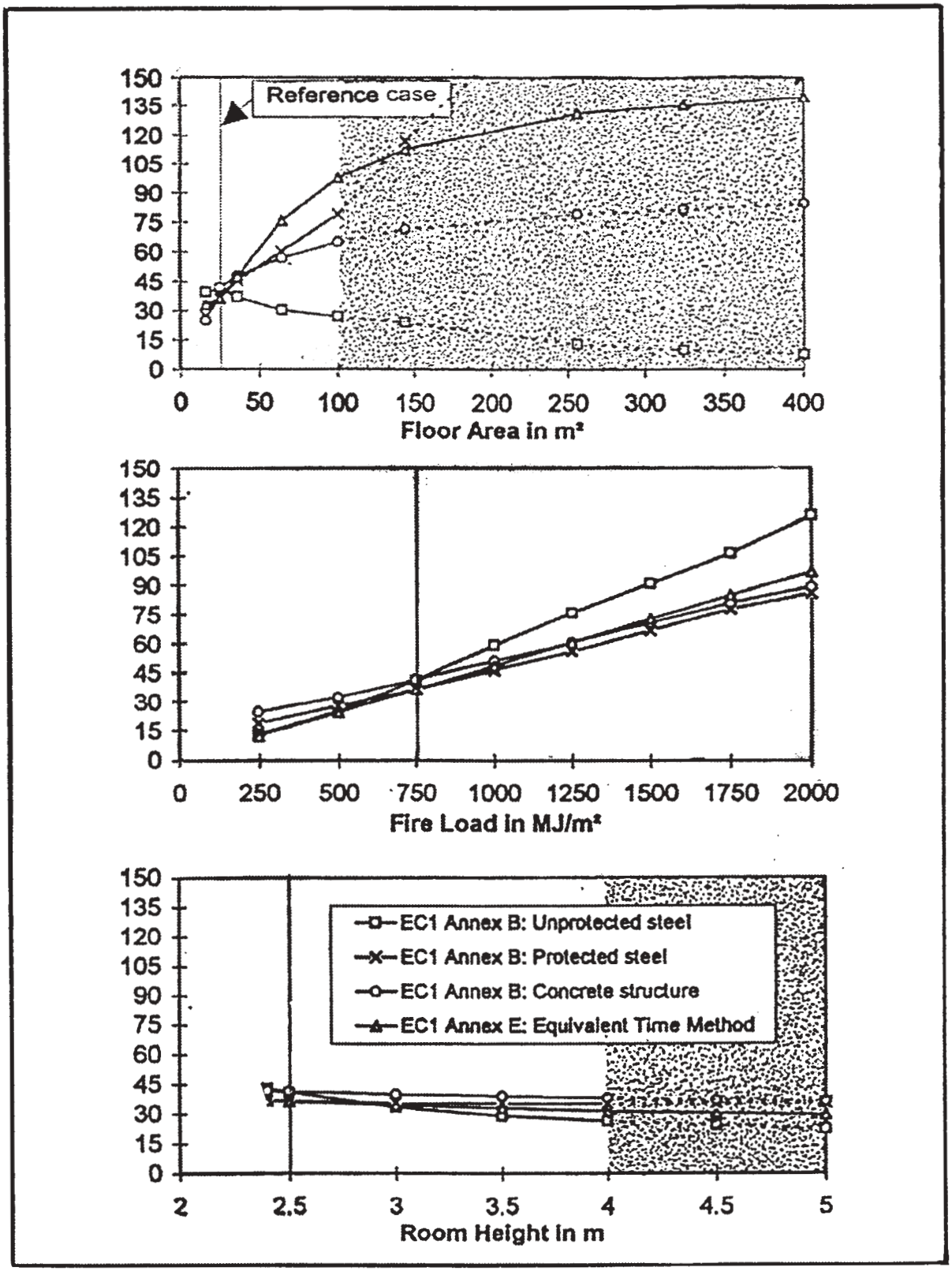


Figure A1.5a: Results of the parametrical study

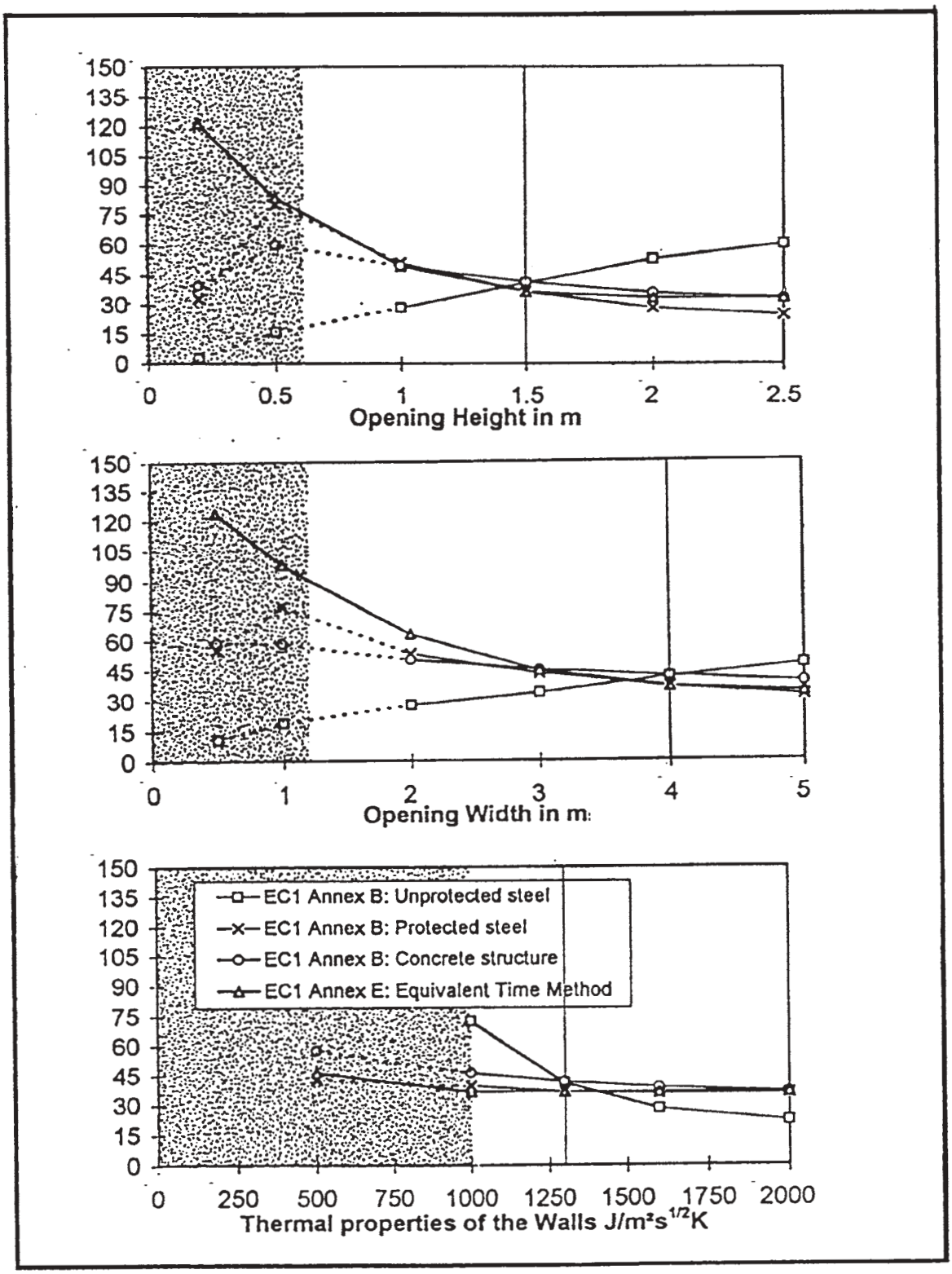


Figure A1.5.b: Results of the parametrical study

A1.6 REFERENCES

[1] Wickström, "Application of the Standard Fire curve for Expressing Natural Fires for Design Purposes".

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

[3] Eurocode 3: Design of steel structures Part 1.2: General rules Strucural fire design, DRAFT ENV 1993-1-2.

[4] Eurocode 4. Design of Composite Steel and Concrete Structures. Part 1.2 : Structural Fire Design, prENV 1994-1-2, CEN , April 1994.

[5] J.B. Schleich, L.G. Cajot, M. Pierre, CEC Agreement 7210-SA / 125, 126, 213, 214, 323, 423, 522, 623, 839, 937 "Competitive Steel Buildings Through Natural Fire Safety Concept" Technical Report n° 1 Semestrial Report (01.07.1994 to 31.12.1994)

[6] J.B. Schleich, L.G. Cajot, M. Pierre, CEC Agreement 7210-SA / 125, 126, 213, 214, 323, 423, 522, 623, 839, 937 "Competitive Steel Buildings Through Natural Fire Safety Concept" Technical Report n° 2 Semestrial Report (01.01.1995 to 30.06.1995)

ANNEX 2: COMPARISON OF EQUIVALENT TIMES FROM EC 1 PART 2.2 ANNEX E AND EXPERIMENTAL TESTS

A2.1 INTRODUCTION

The equivalent time method of the annex E of Eurocode 1 part 2.2 is presented. The equations proposed by the EC1 are described. A database of 49 fire tests is used to validate the method. A method is proposed to transform temperature-time curve measured during test into equivalent time of fire exposure. The comparison of the equivalent times obtained on one hand by the EC1 method and on the other hand by calculations from temperature measurement during fire test is presented for two steel profiles, one unprotected and another one protected.

The point of this work is to compare the method of equivalent time described in the annex E of Eurocode 1 part 2.2 and the natural fire tests which were collected in a database (see chapter 5). In order to do this, a "real equivalent time" has been calculated for each test using as data the temperature time curve measured during the test. Also for each test the Eurocode method has been applied using the real conditions applied to the test (fire load, geometry of the compartment, wall characteristics...).

A2.2 THE EQUIVALENT TIME METHOD FROM EC1 PART 2.2 ANNEX E

Annex E of Eurocode 1 offers a simple equation (A2.1) to determine the required fire resistance time $t_{e,d}$ for a compartment, equivalent to the same duration of an ISO curve fire.

$$t_{e,d} = q_d \, k_b \, w_f \qquad \text{(A2.1)}$$

Before starting the calculation, it is necessary to determine the floor area of the compartment A_f as well as the total fire load $Q_{fi,k}$,mainly depending on the combustibility of the component parts and of the stored material. Annex D of EC1 part 2.2 can be applied for this purpose. The design fire load density $q_{f,d}$ can be obtained from the multiplication of the characteristic fire load q_k by the safety factors γ_n and γ_q for the accepted failure risk in the case of fire and the influence of active fire measures, equation (A2.2).

$$q_d = \gamma_q \, \gamma_n \, q_k = \gamma_q \, \gamma_n \, \frac{Q_{fi,k}}{A_f} \qquad \text{(A2.2)}$$

The conversion factor k_b in equation (A2.1) accounts for the heat transfer in the neighbouring component parts of the compartment. It depends on the thermal properties of the walls and ceilings of the enclosure, see table E.1 of [2].

The ventilation factor w_f can be calculated by the following equation ;

$$w_f = \left(\frac{6}{H}\right)^{0,3} \left(0,62 + 90(0,4 - \alpha_v)^4 / (1 + b_v \alpha_h)\right) \geq 0,5 \qquad \text{(A2.3)}$$

This equation depends on the height of the compartment H and on the ratios of the vertical (α_v) and horizontal (α_h) opening areas to the floor area A_f.

The dimensionless factor b_v can be determined by the following equation ;

$$b_v = 12{,}5\left(1+10\alpha_v-\alpha_v^2\right) \geq 10 \qquad \text{(A2.4)}$$

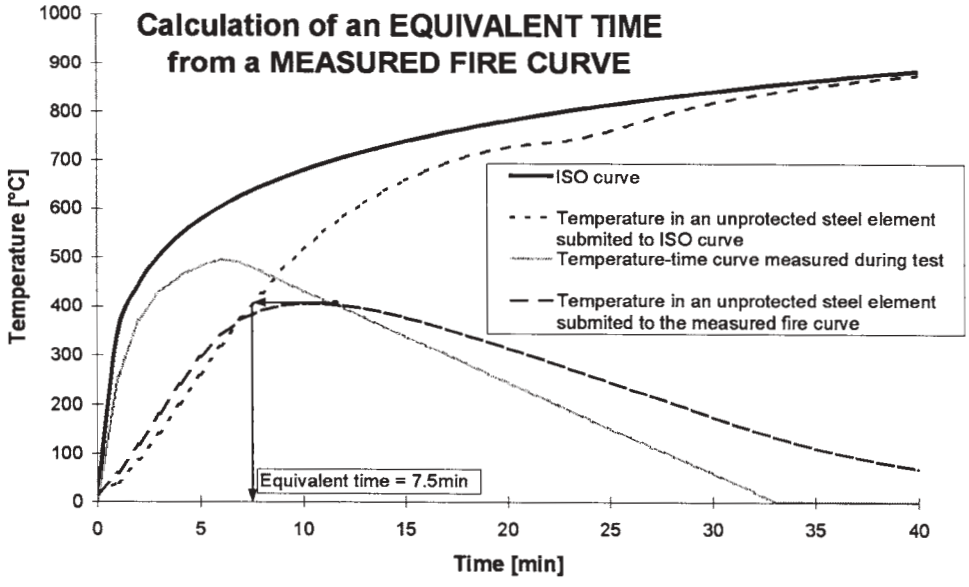
A2.3 PRINCIPLE OF THE CALCULATION OF THE EQUIVALENT TIME OF A NATURAL FIRE TEST TO THE ISO FIRE CURVE

In order to make a comparison between the equivalent time methods and the natural fire test, we have to transform the temperature curve measured during tests into equivalent times. This is done by calculations of temperatures in a structure and observation of the maximum temperature reached by this structure. Two structures have been chosen here;

- *Unprotected steel section.* In this case, the calculation of the uniform temperature is made by the method described in § 4.2.5.1. of Eurocode 3 : Part 1-2 [3]. A massivity of 211 m^{-1} was chosen corresponding, for example, to a HE 200 A section.
- *Protected steel section.* The same massivity is taken as for the unprotected section. The lightweight insulating material has the following properties: c_P = 850 J/(kgK); λ_P = 0,15 W/(m^2K); ρ_P = 300 kg/m^3 ; thickness = 20 mm. Those characteristics are similar to vermiculite. Here the calculation of the uniform temperature is made by the method described in § 4.2.5.2. of Eurocode 3 : Part 1-2 [3].

For the thermal calculations, steel thermal properties are taken from Eurocode 4 : part 1-2 [4].

The temperature in the structures submitted to the ISO curve is first calculated as a function of time. The same calculation is made for the same structures submitted to the natural fire curves obtained from annex B. In each case, the maximum temperature obtained in a structure submitted to a parametric temperature-time curve is reported on the corresponding curve obtained by the first calculation when the structure was submitted to the ISO curve. The moment when this temperature is obtained is defined as the equivalent time.

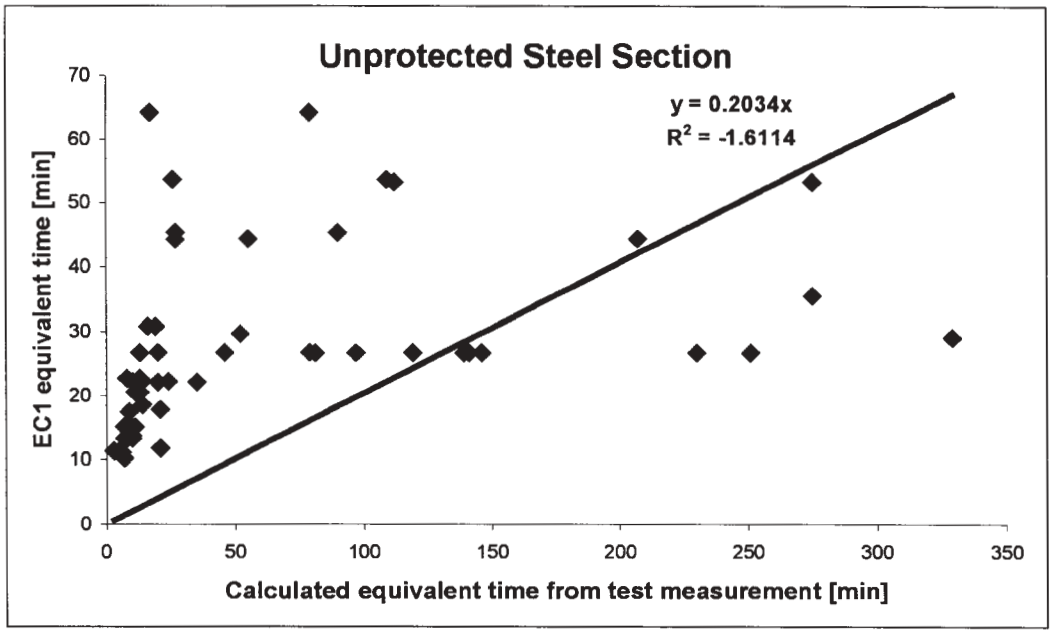


In other words, the equivalent time is the time during which a defined structure has to be submitted to the ISO fire curve in order to obtain, in the structure, the same effect (maximum temperature) as the natural fire curve would have produced.

A2.4 COMPARISONS OF THE RESULTS

The results of all the calculations have been reported on 2 graphs. One graph concerns the calculations in the **unprotected** steel profile and the other concerns the calculations in the **protected** steel profile.

UNPROTECTED STEEL PROFILE

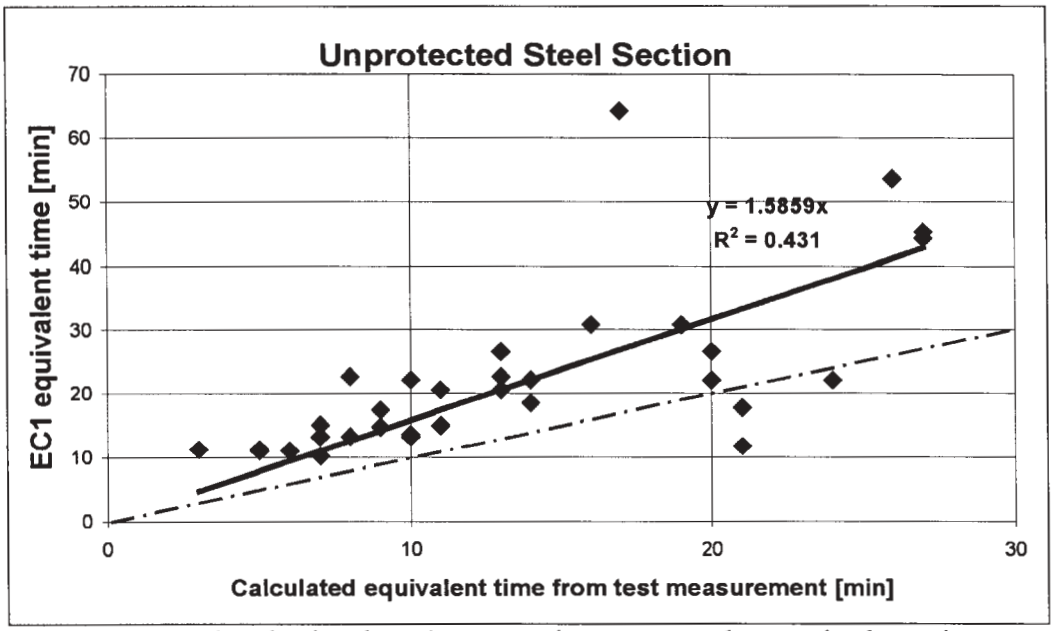


The correlation is bad when all the results are taken into account. However the results for equivalent times calculated from test measurement included between 0 min and 30 min seems to correlate quite well.

The wide distribution of equivalent times that are upper than 30 min has no consequences on the safety of constructions because after 30 min of ISO fire, the temperature of an unprotected steel section is so high that the resistance of this profile becomes negligible. For unprotected section there is thus nearly no difference between equivalent times of 30 min and of 60 min. Moreover for these tests the equivalent time obtained with the annex E of EC1 part 2.2 is at least equal to about 30 min.

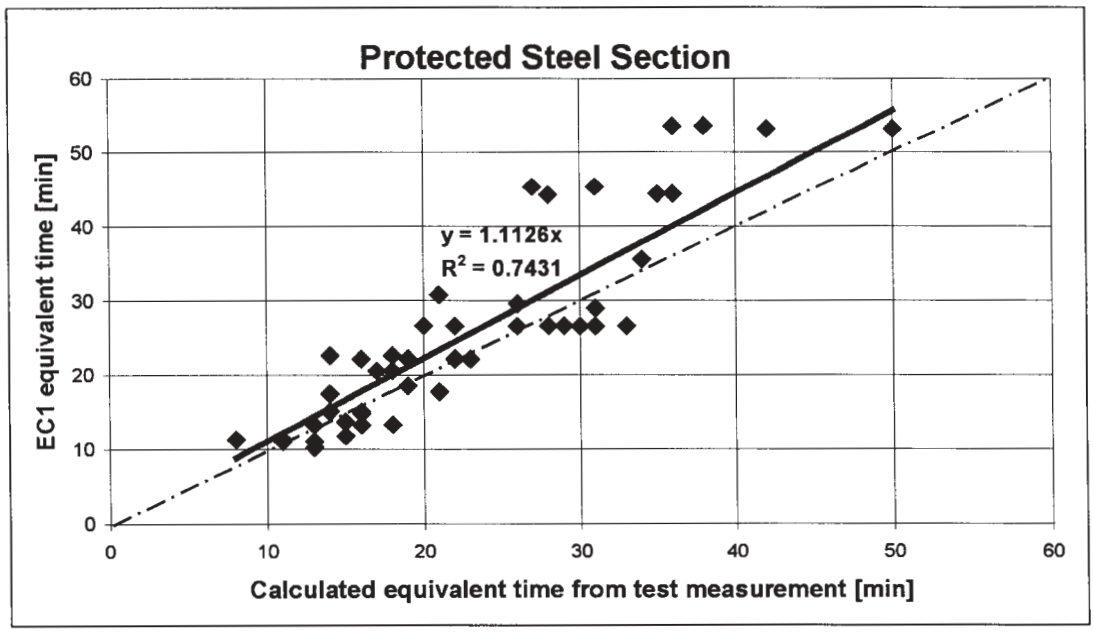
The wide distribution is also due to the fact that after 30 min of ISO fire, the slope of the temperature time curve in an unprotected steel section is very weak. Than for a small difference of maximum steel temperature in the section submitted to the natural fire curve there is a wide difference in the calculated equivalent time.

If we forget about the test where the equivalent time (calculated from test) is greater than 30 min we can plot the following graph.



A good correlation is obtained and except in 3 cases the equivalent time method is safe.

PROTECTED STEEL PROFILE



In case of a protected steel profile the correlation between the "real" equivalent time and the equivalent time calculated with the EC1 part 2.2 method is very good.

A2.5 CONCLUSIONS

The method of annex E of EC1 part 2.2 gives very good results in case of protected steel structures. For unprotected steel structure the method is less efficient but seems to give reasonable results.

These conclusions are of course limited to the conditions covered by the database and to the steel profiles above mentioned . In case of protected steel profile, it has been shown in [4] that the influence of the steel profile on the equivalent times is not important.

A2.6 REFERENCES

[1] Eurocode 1 - Basis of design and actions on structures - Part 2-2: Actions on structures - Actions on structures exposed to fire. ENV 1991-2-2, CEN, Brussels, Febr. 1995.

[2] Database of Natural Fire Test, Natural Fire Safety Concept, Technical Report N°7 Semestrial Report, CEC Agreements 7210-SA/125, 126, 213, 214, 323, 423, 522, 623, 839, 937. Period from 01.07.97 to 31.12.97.

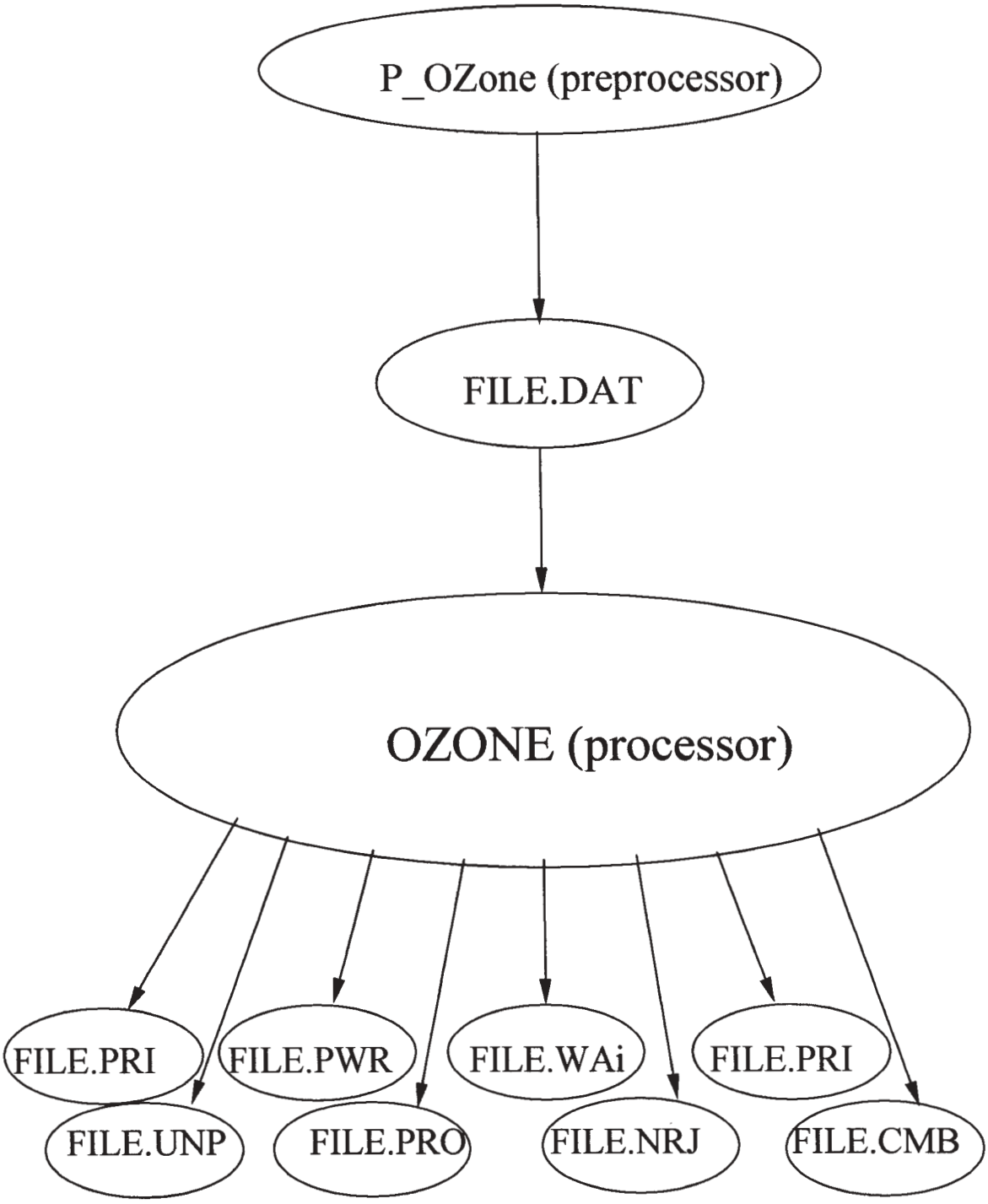
[3] Eurocode 3 : Design of steel structures. Part 1.2 : General rules. Structural fire design. Draft ENV 1993-1-2, CEN, Brussels, may 1995

[4] JM. Franssen, JF. Cadorin, LG. Cajot, JB. Schleich, H. Schweppe, R. Kindmann, Connection between Parametric temperature-time curves and Equivalent time of fire exposure (Annexes B and E of ENV 1991-2-2).

[5] Wickström, Application of the Standard Fire curve for Expressing Natural Fires for Design Purposes.

ANNEX 3: USER GUIDES

A3.1 GENERAL VIEW OF OZONE USER GUIDE



A3.1.1 FILE.DAT

rvolume:	Volume of the compartment	[m³]
Tini:	Initial temperatures	[K]
rPinitial:	Initial pressure	[Pa]
rDHc:	Combustion Heat of the fuel	[J/kg]
timemax:	end of the calculation	[s]
printstep:	time step for printing results	[s]
xtimestep:	maximum time step used by the code during the calculation	[s]
nbwall:	Number of walls	[]
nbmatwall:	Number of material law	[]
nbopen:	Number of openings	[]
irmf:	Type of RHR curve	[]
nbptrmf:	If irhr = 1, number of point used to define the RHR	[]
icomb:	Numer of combustion model	[]
iunpro:	=1 if calculation of the temperature in an unprotected steel section =0 if not	
ipro:	=1 if calculation of the temperature in an protected steel section =0 if not	
iopevol:	=0 if 100% of the openings are opened all the time =1 if step wise evolution function of temperature =2 if linear evolution with temperature	

For each walls:

- **wallarea**: wall area [m²]
- **nbele**: number of elements []
- For each elements:
  - **-rlele**: thickness of each elements [m]
  - **-nmat**: material of each elements []

Rem: The first element of each wall is on the inner side of the wall (hot side)

For each material:

- **rho**: specific mass [kg/m³]
- **rk**: conductivity [W/(m K)]
- **rc**: specific heat [J/(kg K)]
- **repsilint**: relative emisivity of the hot surface []
- **repsilext**: relative emisivity of the cold surface []
- **rhint**: convection coefficient at the hot surface [W/(m² K)]
- **rhext**: convection coefficient at the cold surface [W/(m² K)]

For each openings:

- **rsill**: height of the sill of each opening [m]
- **rsoffit**: height of the soffit of each opening [m]
- **rwidth**: width of each opening [m]

- **rcvent**: Bernoulli coefficient for each opening []

Pyrolysis rate:

a. If irmf = 0 (see figure 1)

- **rmffuel**: maximum value of the pyrolysis rate [kg/s]
- **tplateau**: time from wich the pyrolysis rate is maximum [s]
- **tendplateau**: time from wich the pyrolysis rate is decreasing [s]
- **tendfire**: time at wich the fire finishes [s]

b If irmf = 1, point by point curve.

- **trmf**: time at wich the pyrolysis rate is defined [s]
- **rrmffuel(trmf)**: pyrolysis rate at time trhr [kg/s]

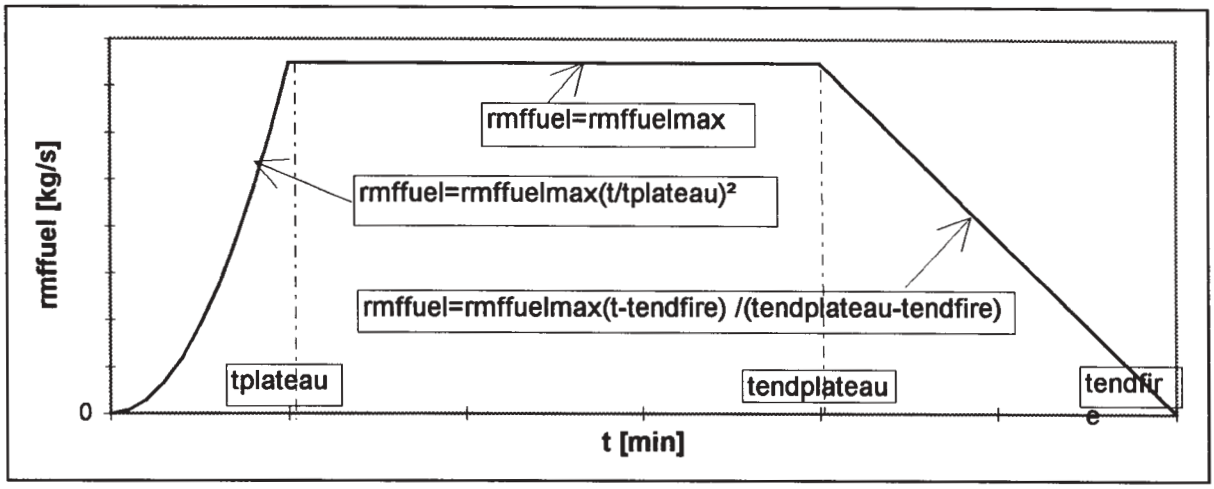


Figure 1

If iunpro = 1

- **AmsurV** section factor of the unprotected profile [m^{-1}]
- **rH**: convection coefficient at the surface [$W/(m^2 K)$]
- **repsilunp** relative emissivity of the profile []

If ipro = 1

- **ApsurV** section factor of the protected profile [m^{-1}]
- **rhop** specific mass of insulation [kg/m^3]
- **rcp** specific heat of insulation [J/(kg K)]
- **rlambdap** conductivity of insulation [W/(m K)]
- **rdp** thickness of insulation [m]

- **ropper1 % of openings opened at Tini**
- **ropT2 temperature at which some openings breaks**
- **ropper2 % of openings opened at ropT2**
- **ropT3 temperature at which some openings breaks**
- **ropper3 % of openings opened at ropT3**

A3.1.2 FILE.OUT

Impression of the data readed by the code in the file.dat.

A3.1.3 FILE.PRI

At each time step the relative pressure at floor level (Δp_{floor} [Pa]) and the temperature in the compartment (T[°C]) are given, the mass balance is also given:

- **p_fl**: relative pressure at floor level Δp_{floor} [Pa]
- **T**: temperature in the compartment [°C]
- **dm**: mass balance = min + mout [kg/s]
- **min**: flux masse of gas going in the compartment [kg/s]
- **mout**: flux masse of gas going out of the compartment [kg/s]

A3.1.4 FILE.WAI

One file is created per wall (ex. for wall n°1: FILE.WA1) with a maximum of 6 files (if there are more than 6 walls, the temperature are printed only for the 6 first walls).
At each time step the the temperature in the compartment (**T** [°C]) and the temperatures at each nodes of the wall (**T_node** [°C]) are given.

A3.1.5 FILE.PWR

At each time step the energy balance is given:

- **RHR**: rate of heat release by the fir [W]
- **Wopen**: rate of heat loss trough the openings by convection of mass [W]
- **Wradopen**:rate of heat loss trough the openings by radiation [W]
- **Wwall**: rate of heat loss to and trough the walls [W]
- **dUdt** =RHR-Wopen-Wradopen-Wwall=derivative of internal energy [W]
- **Wwallconv**: rate of heat loss to and trough the walls by convection [W]
- **Wwallrad**: rate of heat loss to and trough the walls by radiation [W]

A3.1.6 FILE.NRJ

Not used (for the moment)

A3.1.7 FILE.CMB

At each time step the oxygen balance and the energy released in the compartment are given:

- **Efuel**: total energy release by the fire if the fire is fuel controlled [J]
- **Ereal**: total energy release by the fire taken into account in the calculation [J]
- **mOx**: mass of oxygen in the compartment [kg]
- **rmOxin**: mass of oxygen going in the compartment [kg/s]

- **rmOxout**: mass of oxygen going out of the compartment [kg/s]
- **rmffuel**: pyrolysis rate if the fire is fuel controlled [kg/s]
- **rmfvent**: pyrolysis rate if the fire is ventilation controlled [kg/s]
- **rmfreal**: pyrolysis rate taken into account in the mass balance [kg/s]
- **rmburn**: pyrolysis rate taken into account in the energy balance [kg/s]
  RHR = rmburn * rDHc [J/s]
- **d(mOx)dt**:Oxygen balance [kg/s]

A3.1.8 FILE.UNP

At each print step the following information are given:

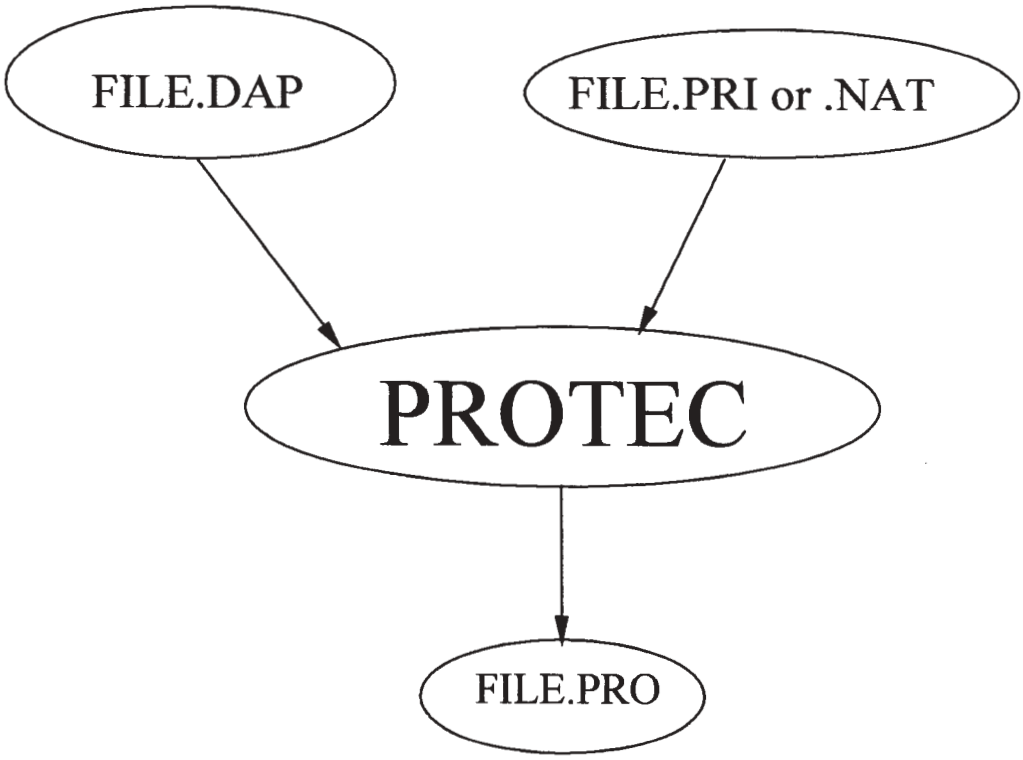
- **time**: [s]
- **T_gas**: temperature in the gas [°C]
- **T_Steelun:** temperature in the steel section [°C]

A3.1.9 FILE.PR0

At each print step the following information are given:

- **time**: [s]
- **T_gas**: temperature in the gas [°C]
- **T_Steelpr:** temperature in the steel section [°C]

A3.2 GENERAL VIEW OF PROTEC USER GUIDE



A3.2.1 FILE.DAP: DATA FILE FOR THE PROTECTED ELEMENT

- nbptnat : number of point used to define the gas temperature (in file .pri or .nat)
- Nbblkline :number of line at the beginning of file .pri or .nat with comments
- Rhoa : specific mass of steel [kg/m³]
- ApsurV section factor of the protected profile [m^{-1}]
- rhop specific mass of insulation [kg/m³]
- rcp specific heat of insulation [J/(kg K)]
- rlambdap conductivity of insulation [W/(m K)]
- rdp thickness of insulation [m]
- timemax end of the calculation [s]
- timestep time step used in calculation (max 10s) [s]
- rpasimp time step for printing results [s]
- timp first print step [s]

A3.2.2 FILE.PRI

This file is an output of **OZONE**. It is asked at the beginning of the run whether you use this file to define the gas temperature or a .NAT file.
Only the temperature in the compartment is used by PROTEC.
In this case **Nbblkline = 1**
See ozone user guide:
At each time step the relative pressure at floor level (Δp_{floor} [Pa]) and the temperature in the compartment (**T**[°C]) are given, the mass balance is also given:

- **p_fl**: relative pressure at floor level Δp_{floor} [Pa]
- **T**: temperature in the compartment [°C]
- **dm**: mass balance = min + mout [kg/s]
- **min**: flux masse of gas going in the compartment [kg/s]
- **mout**: flux masse of gas going out of the compartment [kg/s]

A3.2.3 FILE.NAT

You can put a number of **Nbblkline** lines of comment at the beginning of the file.
Then a number of nbptnat lines with the following format:

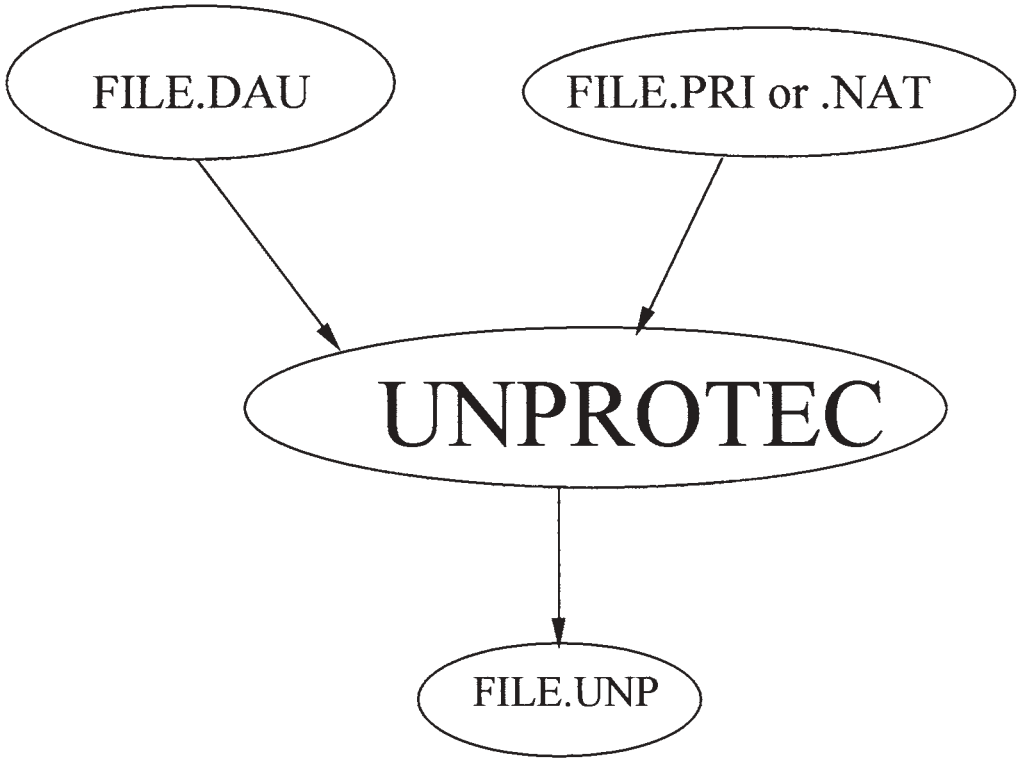
- time, temperature of gas [F10.0,F10.1]

A3.2.4 FILE.PR0

At each print step the following information are given:

- **time**: [s]
- **T_gas**: temperature in the gas (given in dat) [°C]
- **T_Steel:** temperature in the steel section [°C]

A3.3 GENERAL VIEW OF UNPROTEC USER GUIDE



A3.3.1 FILE.DAU: DATA FILE FOR THE UNPROTECTED ELEMENT

- nbptnat : number of point used to define the gas temperature (in file .pri or .nat)
- Nbblkline : number of line at the beginning of file .pri or .nat with comments
- Rhoa : specific mass of steel [kg/m^3]
- AmsurV section factor of the unprotected profile [m^{-1}]
- rH: convection coefficient at the surface [W/(m^2 K)]
- timemax end of the calculation [s]
- timestep time step used in calculation (max 10s) [s]
- rpasimp time step for printing results [s]
- timp first print step [s]

A3.3.2 FILE.PRI

This file is an output of **OZONE**. It is asked at the beginning of the run whether you use this file to define the gas temperature or a .NAT file.
Only the temperature in the compartment is used by PROTEC.
In this case **Nbblkline = 1**

In this case **Nbblkline = 1**
See ozone user guide:
At each time step the relative pressure at floor level (Δp_{floor} [Pa]) and the temperature in the compartment (T[°C]) are given, the mass balance is also given:

- **p_fl**: relative pressure at floor level Δp_{floor} [Pa]
- **T**: temperature in the compartment [°C]
- **dm**: mass balance = min + mout [kg/s]
- **min**: flux masse of gas going in the compartment [kg/s]
- **mout**: flux masse of gas going out of the compartment [kg/s]

A3.3.3 FILE.NAT

You can put a number of **Nbblkline** lines of comment at the beginning of the file.
Then a number of nbptnat lines with the following format:

- time, temperature of gas [F10.0,F10.1]

A3.3.4 FILE.UNP

At each print step the following information are given:

- **time**: [s]
- **T_gas**: temperature in the gas (given in dat) [°C]
- **T_Steel:** temperature in the steel section [°C]

III. WORKING GROUP 2 & 3

III.1 Working group 2

III.2 Working group 3

III.1 WORKING GROUP 2

EQUIVALENT ISO-TIME METHODS

1 INTRODUCTION

The working group 2 was dealing with the equivalent time methods. This working group analysed and compared the methods which exist and are known world-wide.

In detail the following methods were examined (written in the sequence of development).

- M. LAW 1971;
- PETTERSON 1976
- CIB W14 1986;
- HARMATHY 1987;
- DIN 18 230 version 1987;
- DIN 18 230 version 1998;
- EUROCODE EC 1 part 2-2 annex E 1994;
- NEW ZEALAND METHOD 1993.

The "Petterson Method" contains a research report with differentiated influence parameters and a so-called simplified method which has to be distinguished.

It has to be pointed out that this report is in fact provided because the work has been done in the scope of the research but the "Equivalent Time Methods" do not belong to the Natural Fire Safety Method developed and finally proposed here (see main part).

These "Equivalent Time Methods" have been analysed at the beginning of the research because, at this time, it was the only existing methods considering the ventilation conditions and the fire loads. However the weak point is that these methods refer to the ISO-Curve and do not depend on the structure type (protected steel, unprotected steel, reinforced concrete).

2 BASIC FACTORS OF THE EQUIVALENT THEORY

The equivalent theory is based on the basic thought to quantify and to assess fire actions involving the relation to a standard fire accordingly standard temperature curve (ISO curve).

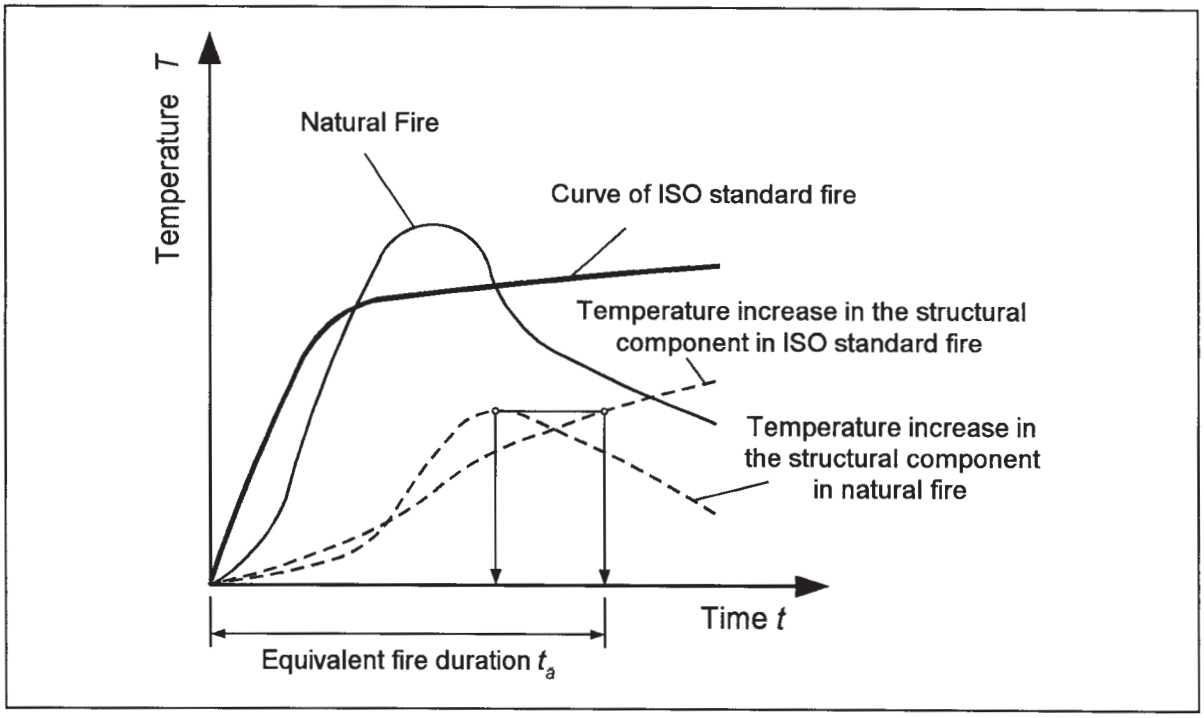
The advantage of the equivalent theory is given with a simple fixing in of the results in conventional fire protecting regulations which are mostly based on standard fire events and secondly for the practical constructor shifting by immediate using of building components which were tested and classified in numberless fire behaviour tests under standard fire conditions.

The relation to standard fires is normally given by the comparison of the effect which is brought about by natural fire respectively by standard fire in the comparison building component.

The maximum temperature measured in comparison building components under natural fire conditions according to the temperature time curve under standard conditions and the fire duration defined as equivalent fire duration in accordance with this temperature is shown in the graph below.

It is conceivable that this method is strongly influenced by the type and substance of the comparison building, which must be approximately analysed according to this research (particularly for calculated verifications of working group 1).

This situation in connection with the existing methods is mostly taken into consideration in the constricted range of application.



The difference between equivalent fire duration and required fire resistance duration is a further important point.

The equivalent fire duration refers to the description above and describes a fire effect of the natural fire in relation to standard fire conditions, so only physical situations are taken into consideration. On the other hand the required fire duration contains further components of the safety concept respectively influences of fire protection measures and/or other safety requirement determined by the department.

3 CONTENTS AND BASIC FACTORS OF THE INDIVIDUAL METHODS

Contents and basic factors of the individual equivalent time methods were collected and summarized in a table (see Annex 1).

First the complete results of this evaluation are described.

All these Methods are similar and some of them have been gradually improved over time.

For all the methods, the formula is similar to the following one:

$$t_e = k_b \cdot q_{d,f} \cdot w_E$$

k_b thermal properties of the enclosure

$q_{d,f}$ fire load density

w_E ventilation conditions

The background of each method has been explained in Annex 1. The intention is to give a general overview of all the methods.

3.1 VENTILATION CONDITIONS; VENTILATION FACTOR W_E

LAW method

The basic equation of this method

$$t_e = K \cdot \frac{L}{\sqrt{A_w \cdot A_{T,Law}}}$$

$$= K \cdot \frac{q_{fd} \cdot A_f}{\sqrt{A_w \cdot A_{T,Law}}}$$

$$= C_{Law} \cdot q_{fd} \cdot w_{Law}$$

where

$$w_{Law} = \frac{A_f}{\sqrt{A_w \cdot A_{T,Law}}}$$

and $A_{T,Law}$ describes the complete surface of the fire compartment without openings and without the ground floor.

- **Petterson, simplified method**

With the converted calculation of the fire load in accordance to the complete surface q_t to the fire load according to the floor area

$$q_t = \frac{q_f \cdot A_f}{A_t}$$

taken from the basic equation

$$t_e = 0{,}067 \sqrt{K_f} \cdot \left(\frac{A_w \cdot \sqrt{h_w}}{A_t} \right)^{-½} \cdot q_t$$

with influencing ventilation relations as

$$w_{Pet} = \sqrt{\frac{A_f}{A_w}} \cdot \sqrt{\frac{A_f}{A_t \sqrt{h_w}}}$$

whereby the complete area of the windows is indicated as A_w and their height as h_w.

- **CIB W14**

The definition of these ventilation relations is identical to the previous Petterson method.

- **DIN 18 230, version 1987**

The discharge heat factor w, which is contained in the basic equation

$$t_e = q_R \cdot c \cdot w_{DIN87}$$

is described as

$$w_{DIN87} = w' \cdot \sqrt{w'}$$

which is exclusively defined in the case of vertical openings as

$$w' = \frac{A_f}{\sqrt{A_t \cdot A_w \cdot \sqrt{h_m}}}$$

$$= \frac{\sqrt{A_f}}{\sqrt{A_w}} \cdot \sqrt{\frac{A_f}{A_t \cdot \sqrt{h_m}}}$$

and correspondingly identical to the ventilation factor DIN 1987 is

$$w_{DIN87} = (w_{Pet})\ 3/2.$$

- **New Zealand Method**

S_c security rating is circumscribed by the basic equation

$$S_c = q_f \cdot w \cdot c_1 \cdot c_2 \cdot c_3 \cdot c_4$$

which does not describe the equivalent fire duration t_e but the required fire duration (see the explanations given at the end of chapter 2 of this report).

The difference is given by the factors c_1 - c_4, so that the definition of the discharge heat factor

$$w_{ZEA} = \frac{A_{df}}{A_{dt}\left(\frac{A_w \cdot \sqrt{h_w}}{A_{dt}}\right)^{0,5}}$$

as known

$$\frac{\sqrt{A_{fZEA}}}{\sqrt{A_w}} = \sqrt{\frac{A_{fZEA}}{A_t \cdot \sqrt{h_w}}}$$

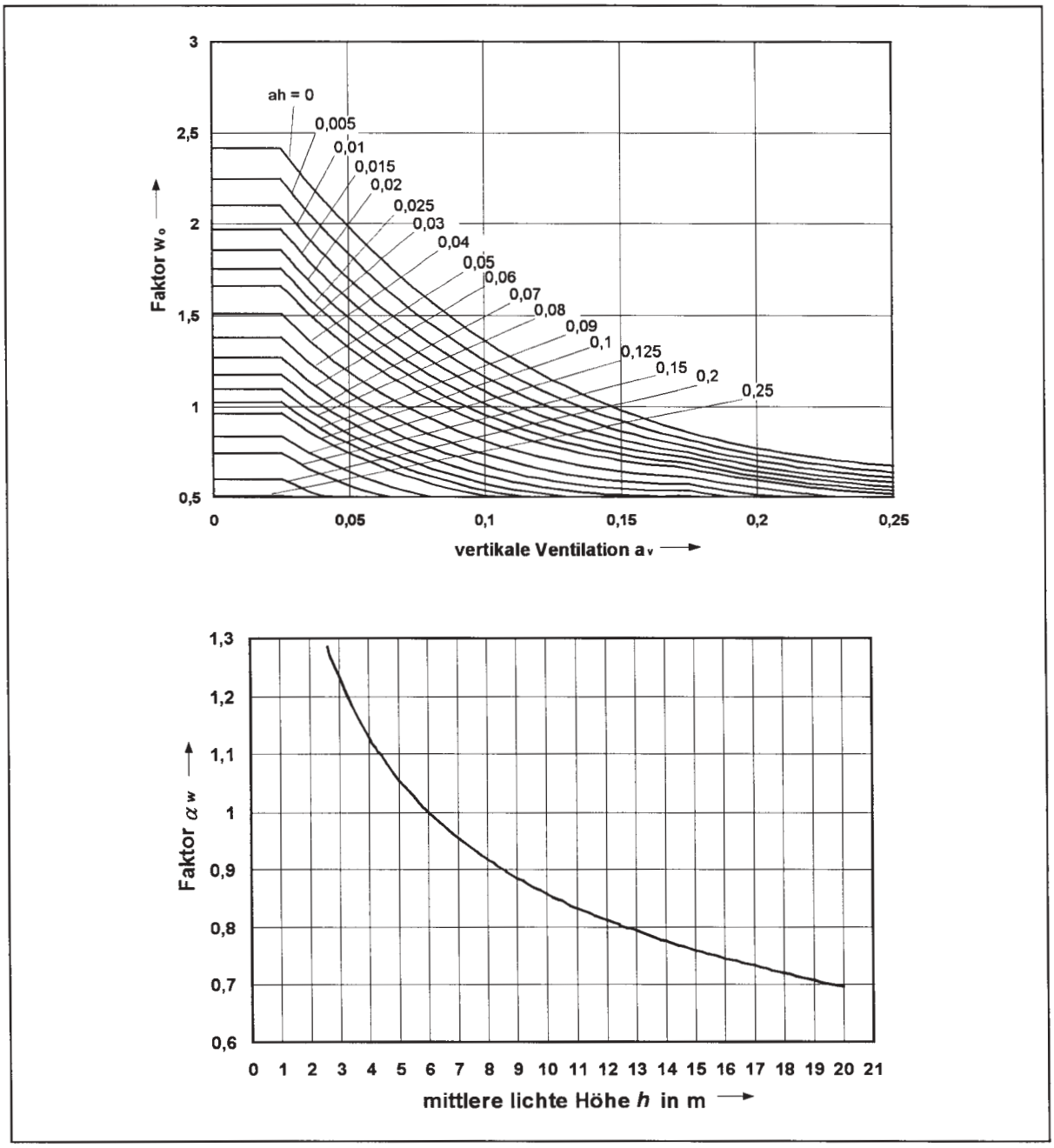
that leads to the beginning of the Petterson method.

- **DIN 18 230, version 1998**

The equivalent fire duration in the DIN 1994 is written as

$$t_e = q_R \cdot c \cdot w$$

analogue to the version 1987, DIN 18 230; taking different thermal dynamic calculations as a basis for determining of the discharge heat factor w. These are shown in a table.



Translation: Faktor = factor; vertikale Ventilation = vertical ventilation; mittlere lichte Höhe = middle clear height.

- **Eurocode 1 part 2-2 annex E**

The basic equation which is written as

$$t_{e,d} = q_{f,d} \cdot K_w \cdot w_f$$

contains the ventilation factor w_f that is defined as

$$w_f = \left(\frac{6,0}{h} \right)^{0,3} \cdot \frac{0,62 + 90 \cdot (0,4 - \alpha_v)^4}{1 + b_v \cdot \alpha_h} \geq 0,5$$

according to the equation 3 of EC 1 part 2-2 annex E.

This formula leads to the same results as the graphically evaluating according to DIN 18 230, version 1998.

3.2 FIRE LOAD ; $q_{d,f}$

The fire load density described - by the previous methods - has to be understood as the mass of combustible substances which is multiplied by its calorific value and divided by the area A_f

$$q_f = \frac{\Sigma (M_i \cdot H_{ui})}{A_f}$$

A combustion factor m is added in the method of DIN 18 230 which takes due consideration the specific combustion characteristic according to the configuration in which they are stored.

As a further difference should be noticed that the fire load is given as kWh/m² whereas the unit MJ is used by the other methods.

With reference to the consideration - according to the New Zealand method - of a designed fire load $q_{f,d}$ referred to a part of an area and which should take into large compartments into consideration.

3.3 INFLUENCE OF THERMAL PROPERTIES; k_b

The consideration of the substances of the surfacing walls and ceilings is implanted to the method described above with exception of the LAW method.

A comparison of values for the factor c (or k_b) depending on the thermal properties b for the Petterson method and CIB W14 method is shown in the table below. Following by the c-factors (DIN 18 230 version 1987) in the declared form and in similar units.

	factor c in $\left[\frac{\text{min} \cdot \text{m}^2}{\text{MJ}}\right]$	
b in $\left[\frac{\text{J}}{\text{m}^2 \cdot \text{s}^{-½} \cdot \text{K}}\right]$	**CIB W14**	**PETTERSON** $c_{Pet} = \sqrt{k_f}\ 0{,}067$
$b > 2.500$	0,05	$\sqrt{0{,}5} \cdot 0{,}067$
$720 \leq b \leq 2.500$	0,07	$\sqrt{1{,}0} \cdot 0{,}067$
$b < 720$	0,09	$\sqrt{2{,}0} \cdot 0{,}067$

DIN 18 230 V '87			
original units		converted units	
b	**c**	**b**	**c**
$\left[\frac{\text{W} \cdot \text{h}^{½}}{\text{m}^2 \cdot \text{K}}\right]$	$\left[\frac{\text{min} \cdot \text{m}^2}{\text{kWh}}\right]$	$\left[\frac{\text{J}}{\text{m}^2 \cdot \text{s}^{-½} \cdot \text{K}}\right]$	$\left[\frac{\text{min} \cdot \text{m}^2}{\text{MJ}}\right]$
> 42	0,15	2520	0,042
$12 \leq b \leq 42$	0,20	$720 \leq b \leq 2.520$	0,055
$b < 12$	0,25	720	0,069

4 COMPARISON OF METHODS; PARAMETER SKETCH

The different methods were finally subjected to a parameter sketch whereby an evaluation occurred for defined values of the working group 1.
Following parameters for the calculations by the values of the "reference case"

base area A_r	=	25 m²
room height H	=	2,50 m
fire load q_F	=	750 MJ/m²
window Height h_w	=	1,50 m
sill of the opening h_S	=	0,5 m
window width w	=	4,0 m
thermal property b	=	1.300

The graphical evaluation of this analysis is enclosed in Annex 2; the reference case in the graphs is marked out.

The realized comparison calculations partly show clearly different results of the single calculations, which, however, may be explained through the fact, that, several times, the field of application for the single methods has not been considered.

Several differences may be explained, since the definition of the "time equivalent" is not identical in all methods. However, systematic differences will get clear, for example in the analysis of the consideration of ventilation influences. With this, the most procedures show higher equivalent fire durations with getting smaller opening cross-sections; even the New Zealand Code considers a case arrangement of ventilation-controlled fire with corresponding smaller equivalent fire duration.

A graphical analysis is shown in annex 2.

5 APPLICATION OF DIN 18 230 TO MORE THAN 3.000 CASES

Whereas the most of the above-mentioned procedures essentially represent basing one upon another steps in a pure scientific handling, the procedure according to DIN 18 230, draft of 1987, has been intensively cited for the permission of industrial buildings in the procedure of building licenses in Germany. A data basis of more than 3.000 cases is available for the author, of which the essential findings are gathered in the following. With this, "unfiltered" fire load investigations of an engineer office are analysed for the following consideration, which have flown in corresponding licensing documents finally. Since, as a rule, calculations with DIN 18230 shall prove facilitations of the basis demands for the building owner, this results in the fact, that the basis data material may not necessarily be representative for the whole German industrial buildings. However, the existing data reveals, up to now, the most extensive compilation of fire technical relevant data regarding industrial buildings in Germany.

5.1 ANALYSIS OF COMPARTMENT AREAS

Figure 5.1.1 shows the distribution of frequency of the fire fighting compartment areas. It gets clear, that, in about 45% of the investigations, the fire load considerations have been realized on areas up to 2.000 m². With this, it is a matter of the valuation of local conditions, like point fire loads, or of the spot check-like ascertainment of data. The fire fighting compartment area was only in 10% of all investigated cases more than 7.000 m² and only in 5% of all cases more than 11.000 m². This relation for greater class width gets clearer in Figure 5.1.2.

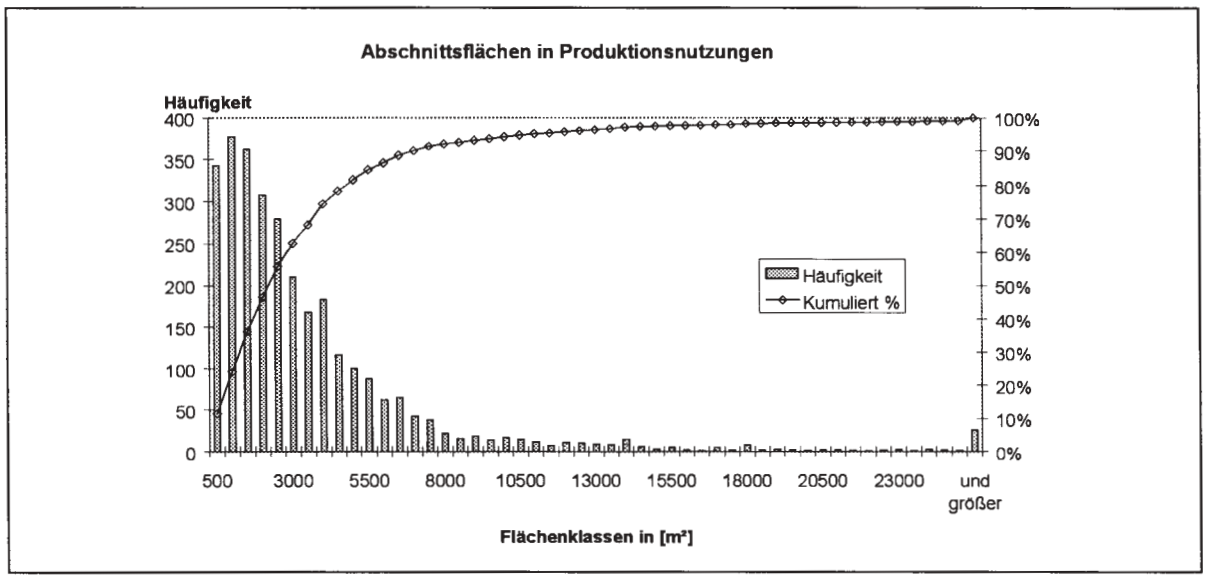


Figure 5.1.1

Translation: Abschnittsflächen in Produktionsnutzungen = compartment areas in production use; Häufigkeit = frequency; kumuliert = cumulated; Flächenklassen = area classes; und größer = and bigger.

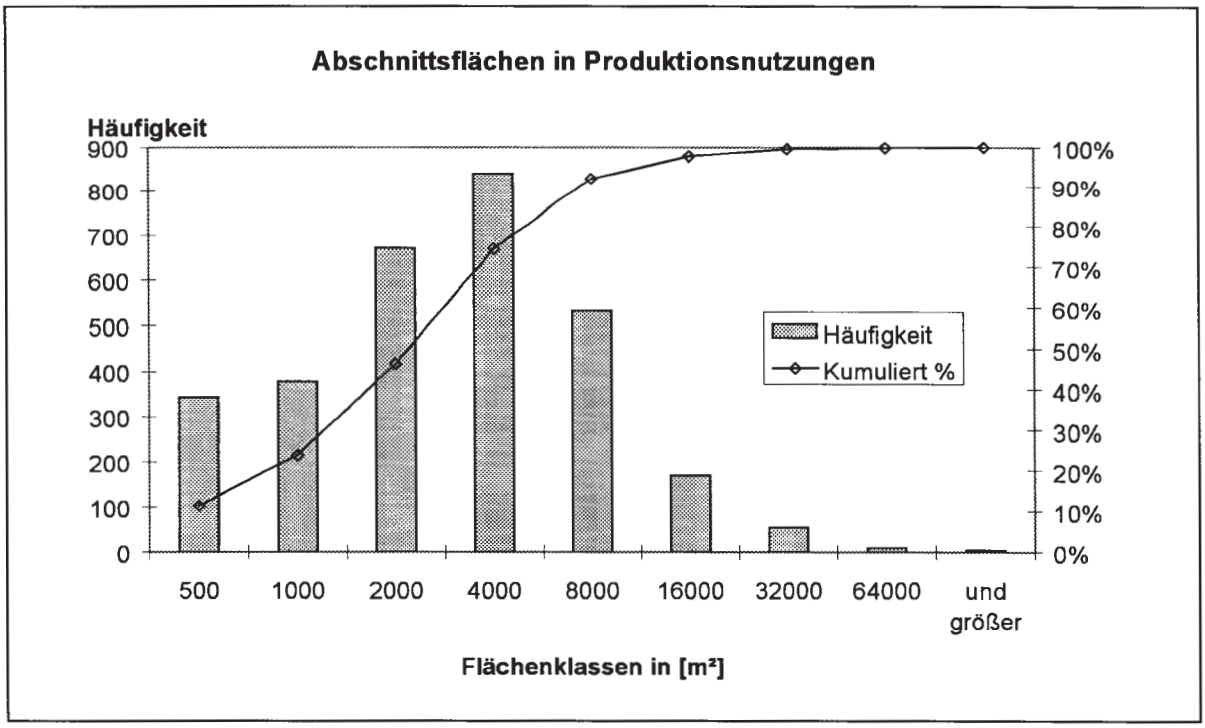


Figure 5.1.2

Translation: Abschnittsflächen in Produktionsnutzungen = compartment areas in production use; Häufigkeit = frequency; kumuliert = cumulated; Flächenklassen = area classes; und größer = and bigger.

5.2 ANALYSIS OF THE VENTILATION CONDITIONS

The distribution of frequency of the chargeable horizontal height openings results from Figure 5.2.1, the vertical heat openings from Figure 5.2.2. In this draft, the factors are:

- a_h = area of the horizontal opening areas (in the roof) divided by ground floor;
- a_v = area of the vertical openings (openings in the walls) divided by ground floor

It gets clear, that less than 2% horizontal heat openings may be considered in about 40% of all buildings. Regarding the vertical opening areas, about 45% of all buildings have up to 3% vertical opening areas.

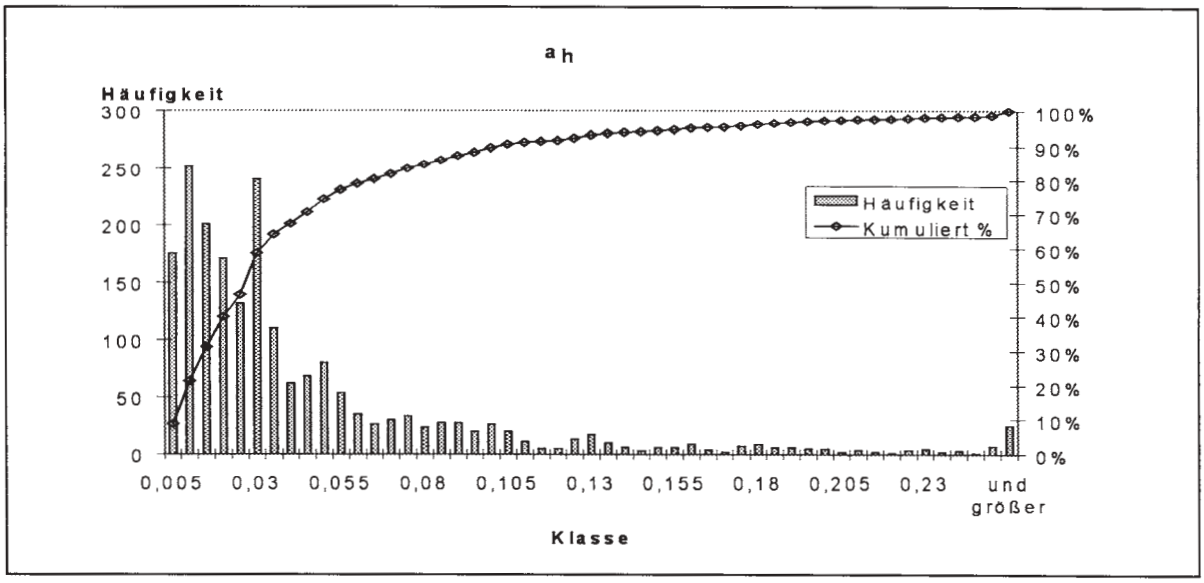


Figure 5.2.1

Translation: Häufigkeit = frequency; kumuliert = cumulated; Klasse = class; und größer = and bigger;

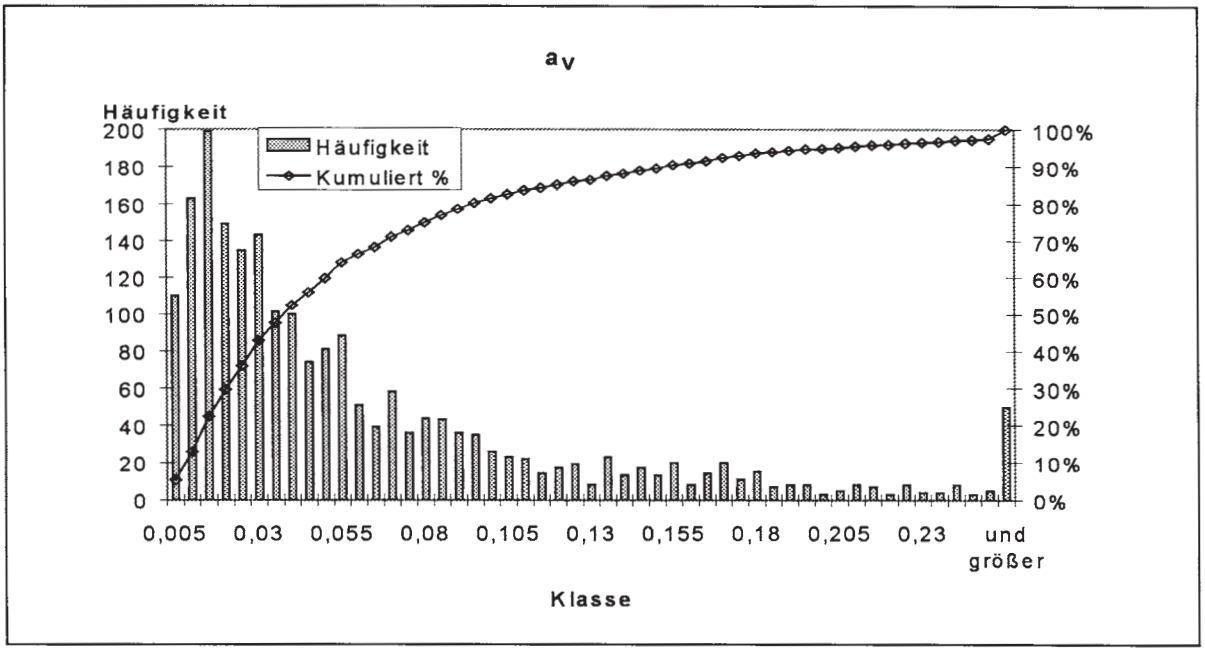


Figure 5.2.2

Translation: Häufigkeit = frequency; kumuliert = cumulated; Klasse = class; und größer = and bigger;

5.3 EVALUATION OF THE BUILDING HEIGHTS

The data regarding the building heights were not registered in all of the 3.000 cases, so that one has to fall back on the following evaluations of complementary assumptions. However, the following evaluation shows, that about 50% of the buildings had a height of up to 9 m.

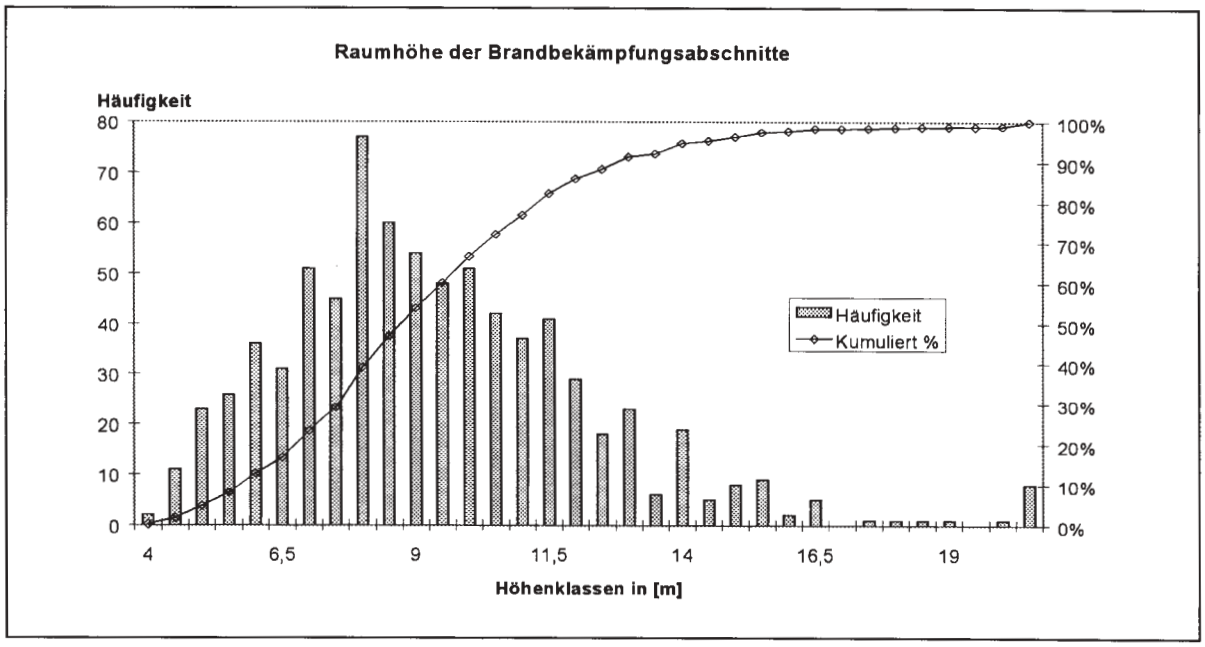


Figure 5.3

Translation: Raumhöhe der Brandbekämpfungsabschnitte = room height of the fire fighting compartments; Häufigkeit = frequency; kumuliert = cumulated; Höhenklassen = height classes.

5.4 EVALUATION OF THE ASCERTAINED MATHEMATICAL FIRE LOADS

The values of the ascertained mathematical fire loads QR (kWh/m²) are of essential interest. The distribution of frequency of the ascertained fire load for all data records is shown in Figure 5.4.1. It is of interest to attach the ascertained fire loads to the respective basic fire compartment area. For this reason, the distributions of frequency are, once again, differentiated in this dependence in the following graphics.

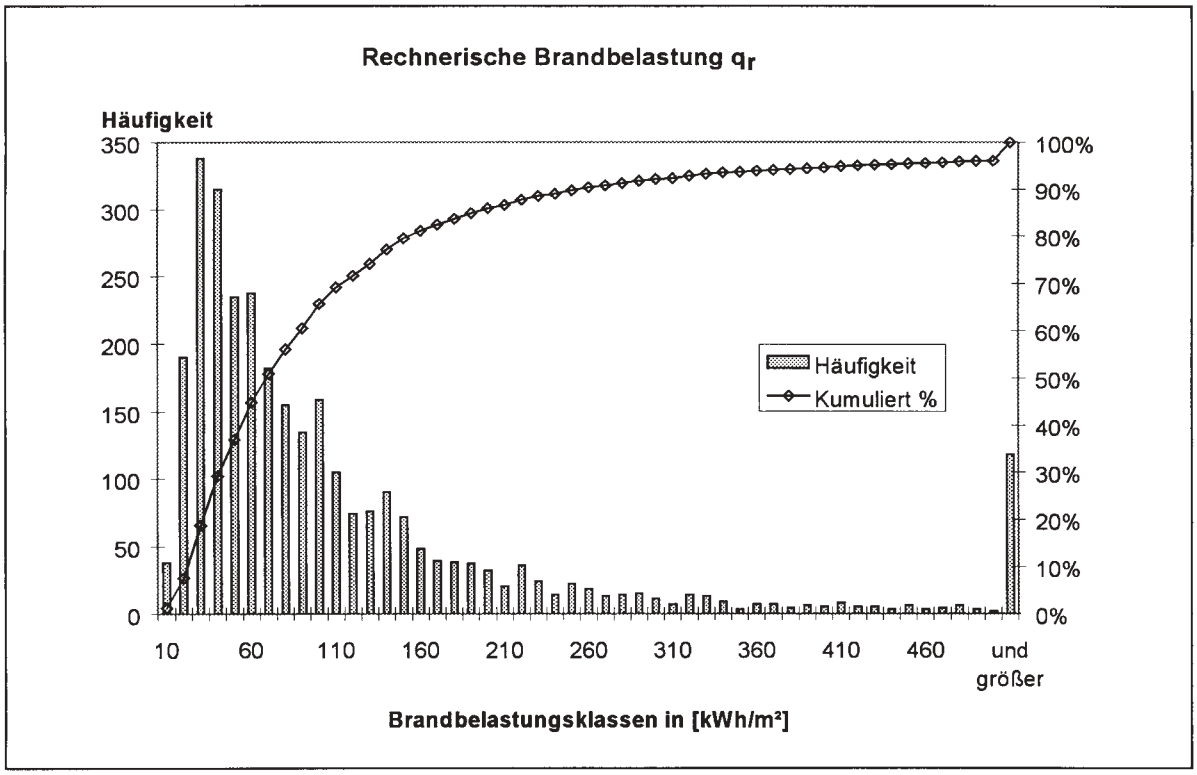


Figure 5.4.1

Translation: Rechnerische Brandbelastung = mathematical fire load; Häufigkeit = frequency; kumuliert = cumulated; und größer = and bigger; Brandbelastungsklassen = fire load classes.

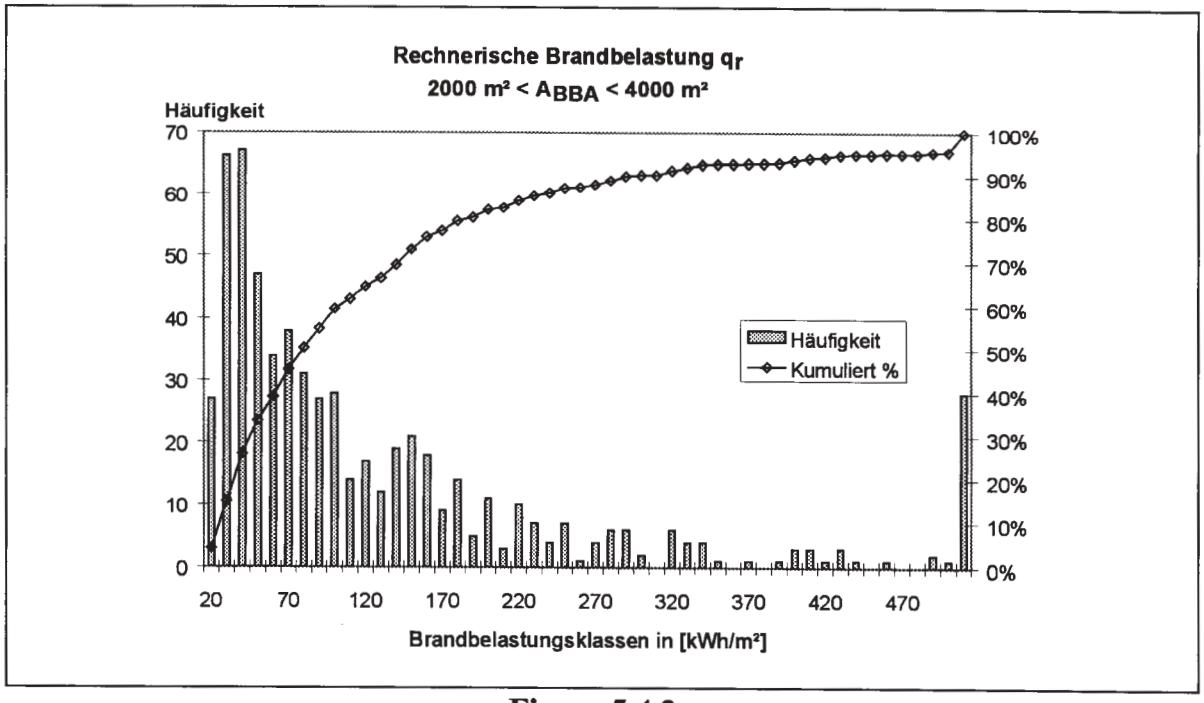


Figure 5.4.2

Translation: Rechnerische Brandbelastung = mathematical fire load; Häufigkeit = frequency; kumuliert = cumulated; Brandbelastungsklassen = fire load classes.

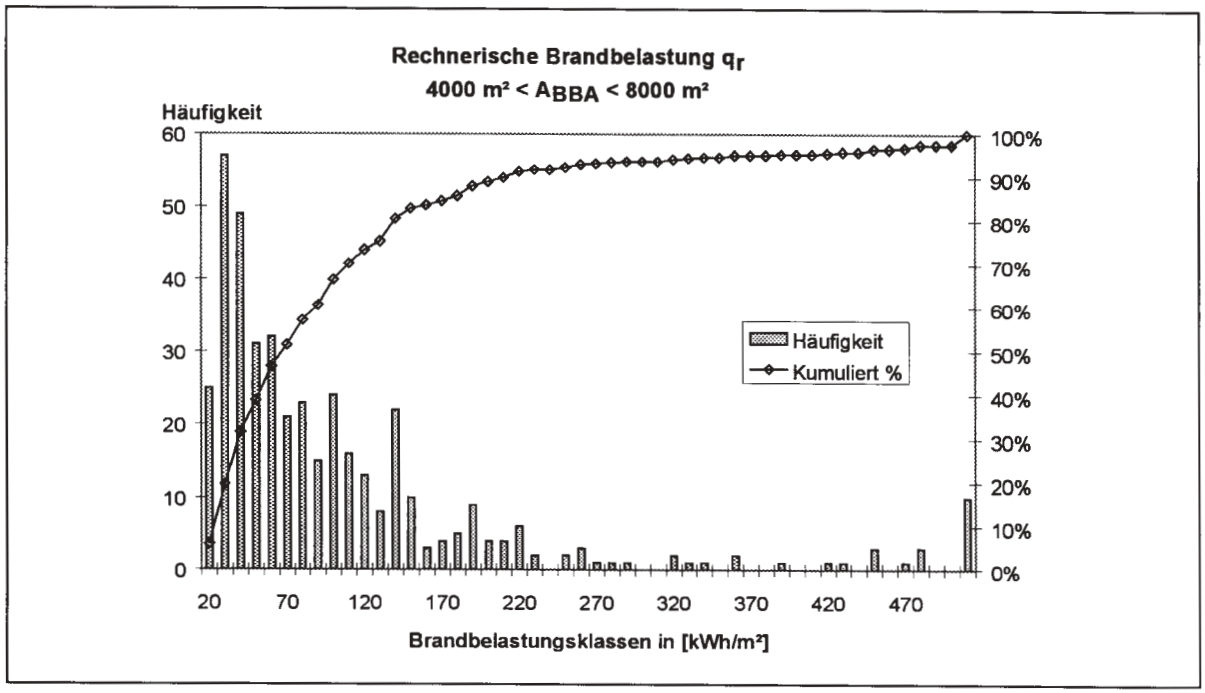


Figure 5.4.3

Translation: Rechnerische Brandbelastung = mathematical fire load; Häufigkeit = frequency; kumuliert = cumulated; Brandbelastungsklassen = fire load classes.

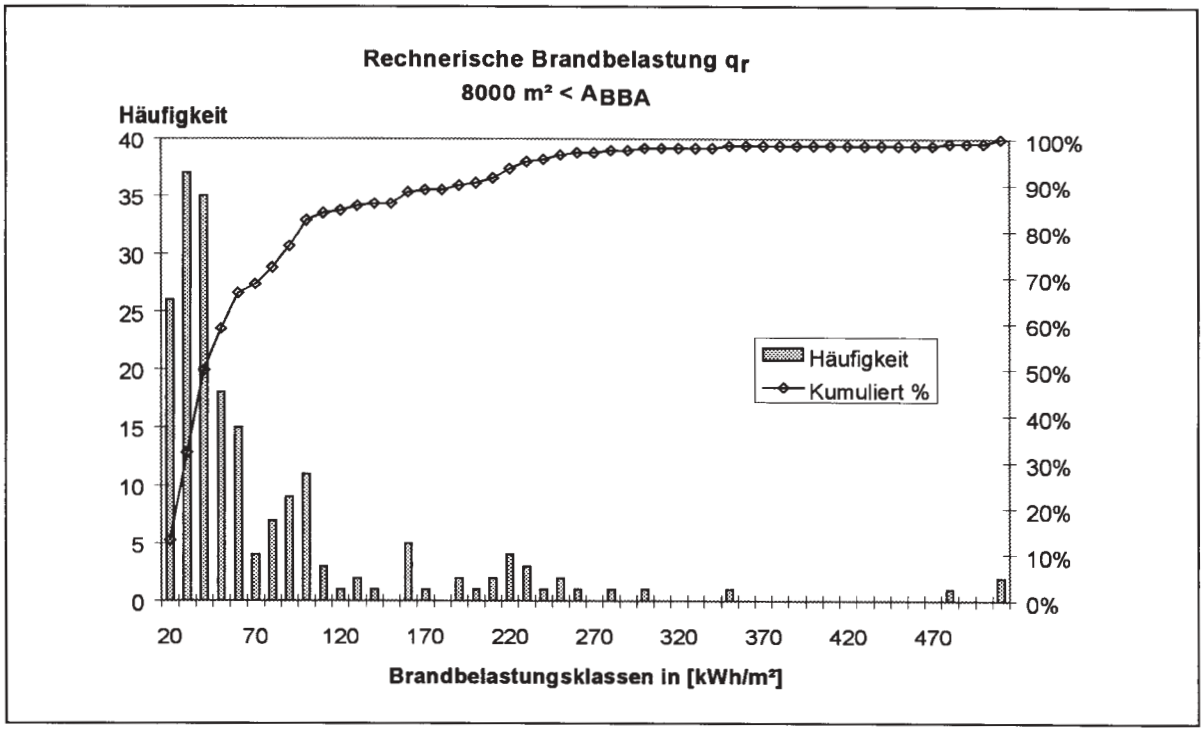


Figure 5.4.4

Translation: Rechnerische Brandbelastung = mathematical fire load; Häufigkeit = frequency; kumuliert = cumulated; Brandbelastungsklassen = fire load classes.

As a résumé, the following tabulation of the fractile data may result.

figure	area	≤ 30 kWh/m²	50 %	85 %
5.4.1	all	20 %	70 kWh/m²	190 kWh/m²
5.4.2	2.000 – 4.000 m²	15 %	80 kWh/m²	230 kWh/m²
5.4.3	4.000 – 8.000 m²	22 %	70 kWh/m²	180 kWh/m²
5.4.4	8.000 – 16.000 m²	25 %	< 50 kWh/m²	160 kWh/m²

6 COMPARING CONSIDERATION OF DIN 18 230, VERSION 1987 AND 1998

6.1 INTRODUCTION

A more scientific founded procedure should be made available with the new version of the norm and the publication as so called "white print version" in May 1998. For this reason, a steady procedure was developed, for example, for the definition of the ventilation conditions, expressed in w-factors, instead of the rating in classes. A comparison, which was determined graphically for different heights of halls, but with a common base of 4.000 m², shows, that higher w-factors are prevailing, which leads, because of the above-mentioned proportionality, at the same time to higher equivalent fire durations and, with this, to an intensification. The evaluation shows, too, that one may find out smaller values for less vertical height openings than with the old version.

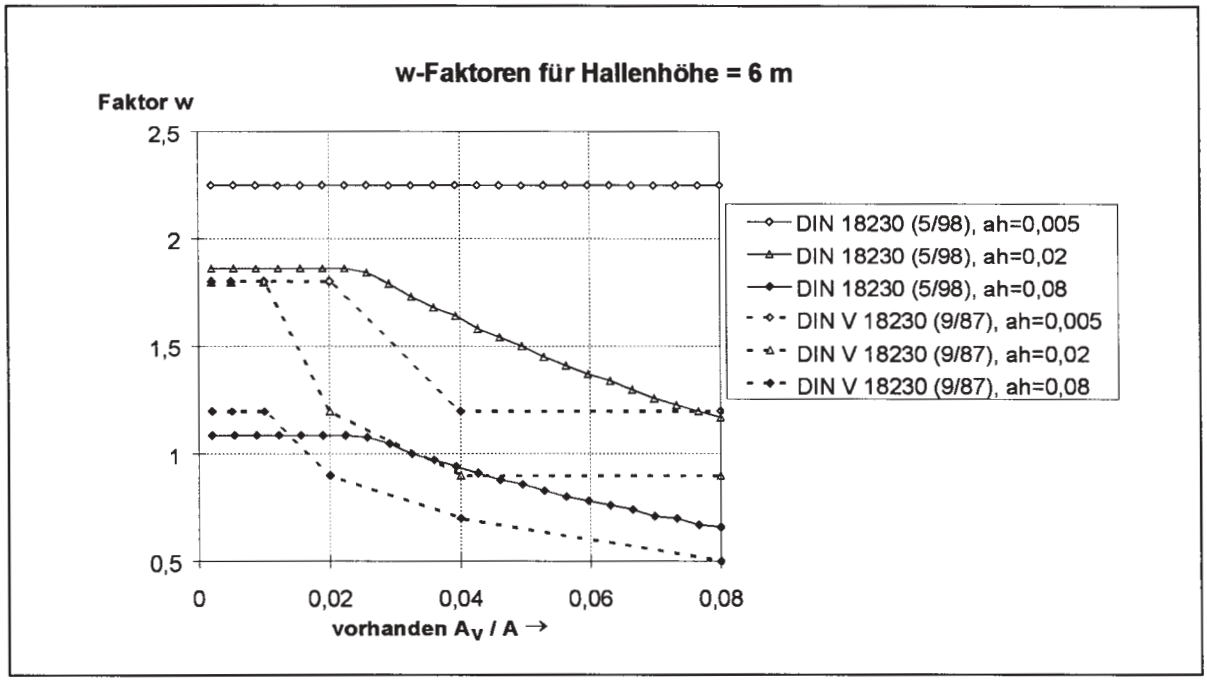


Figure 6.1.1

Translation: Faktor w = factor w; w-Faktoren für Hallenhöhe 6 m = w-factors for a hall height of 6 m; vorhanden = available.

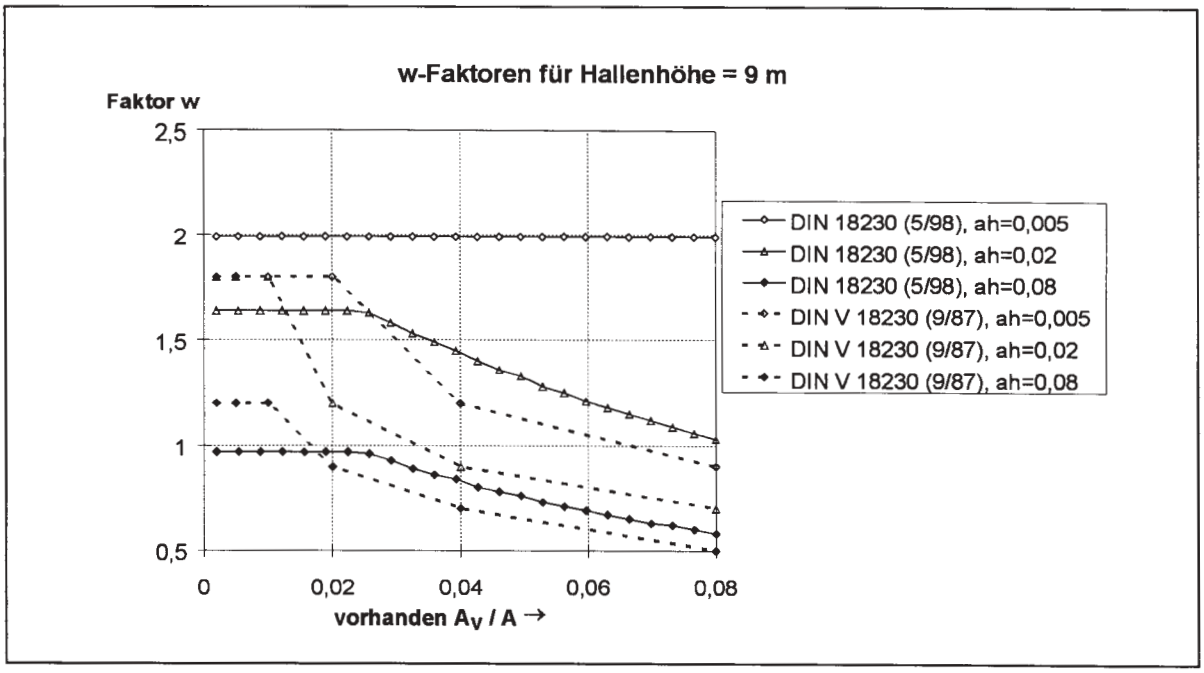


Figure 6.1.2

Translation: Faktor w = factor w; w-Faktoren für Hallenhöhe 9 m = w-factors for a hall height of 9 m; vorhanden = available.

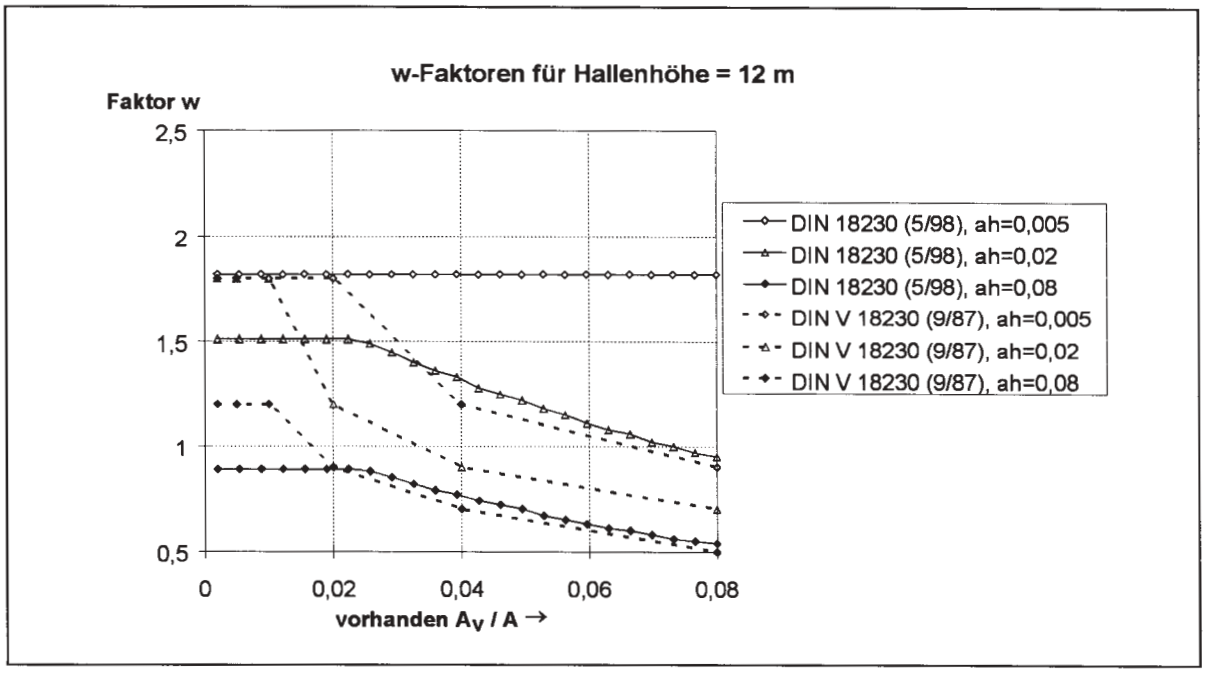


Figure 6.1.3

Translation: Faktor w = factor w; w-Faktoren für Hallenhöhe 12 m = w-factors for a hall height of 12 m; vorhanden = available.

6.2 VARIATION OF THE W-FACTORS BY THE CHANGE OF THE NORM

One determined the unknown building heights of the existing basis data records as h = 6 m in Figure 6.2.1 and as h = 12 m in Figure 6.2.2 for the evaluation of the actual change of the w-factors of real investigated fire fighting compartments in order to limit the spread of changes. Both figures show clearly, that a change of the w-factor up to 50% may result.

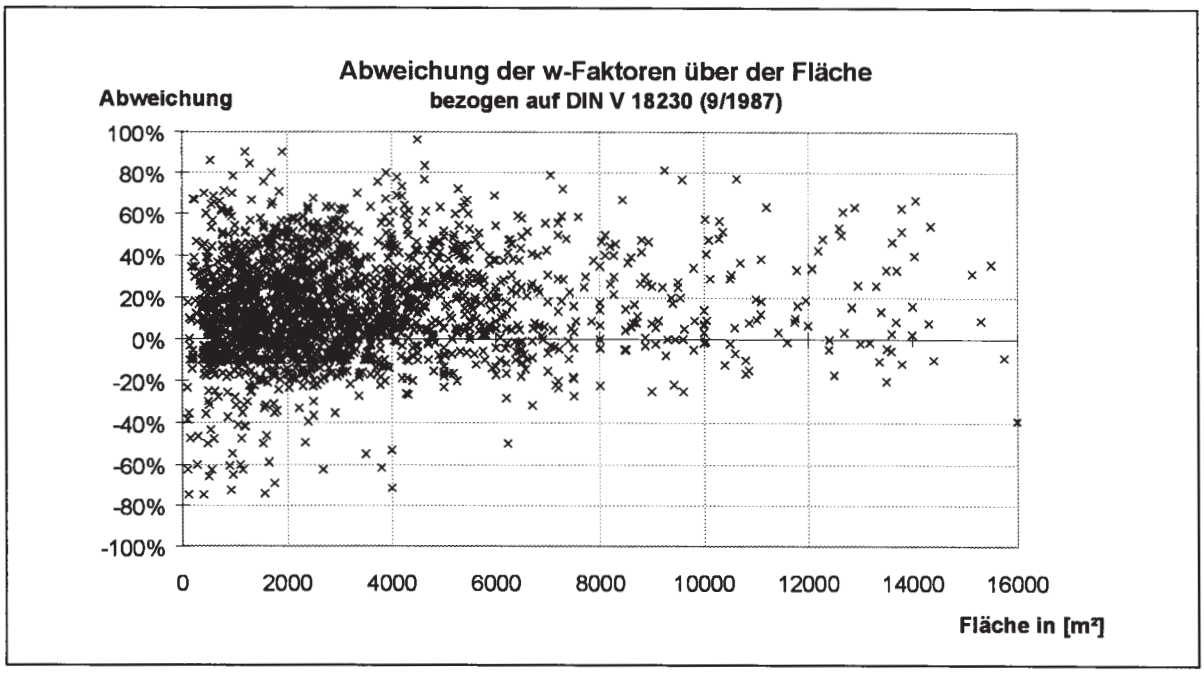


Figure 6.2.1

Translation: Abweichung der w-Faktoren über der Fläche bezogen auf DIN V 18 230 (9/1987) = deviation of the w-factors above the area with reference to DIN V 18 230 (9/1987); Abweichung = deviation; Fläche = area.

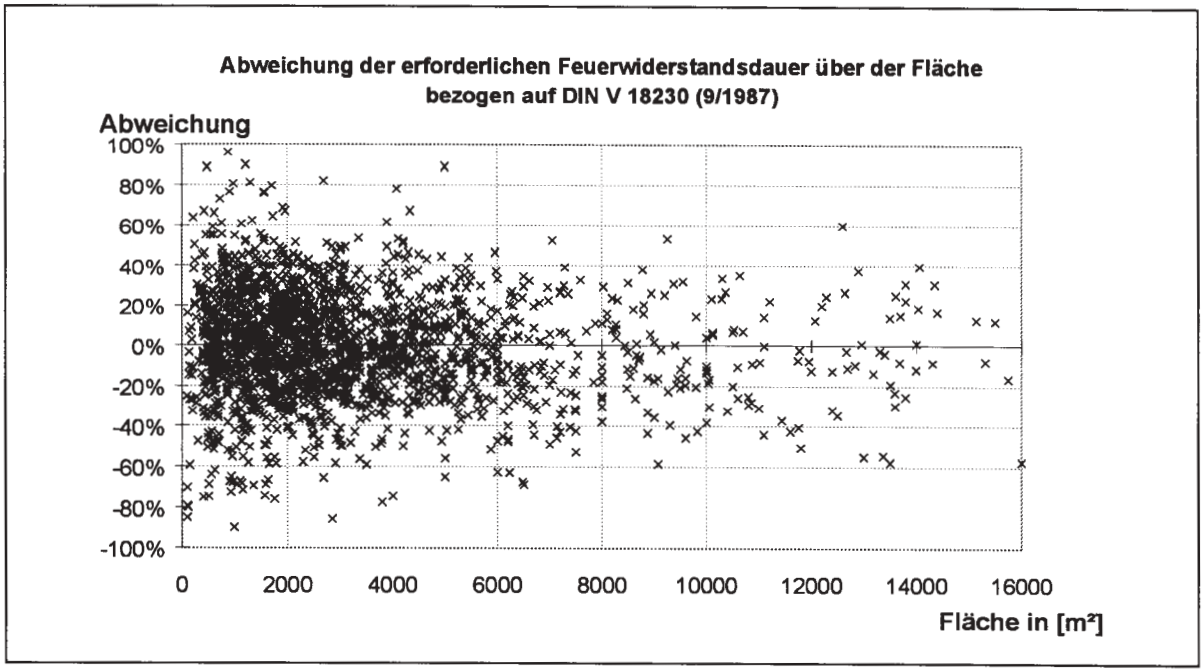


Figure 6.2.2

Translation: Abweichung der erforderlichen Feuerwiderstandsdauer über der Fläche bezogen auf DIN V 18 230 (9/1987) = deviation of the necassary fire resistance duration above the area with reference to DIN V 18 230 (9/1987); Abweichung = deviation; Fläche = area.

6.3 OVERALL CONSIDERATION

One may expect out of the above representations clear effects of the change of the norm of the w-factors and out of the knowledge of the proportionality similar great straggling for the equivalent fire duration or the necessary fire resistance times, which are influenced by the additional safety value. The following Figure 6.3.1, which represents the quotient of the necessary fire resistance time according to the new norm with reference to the old norm version, shows, as it were, parallel to the above-mentioned changes of the w-factor straggling in the area of +/- 50%, regarding erf tF.

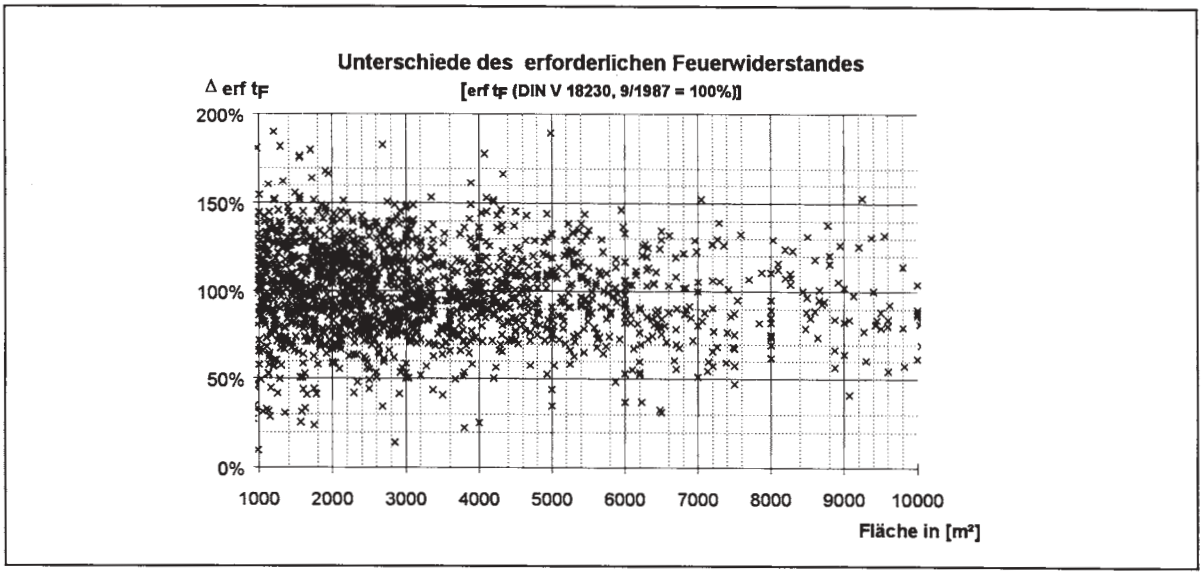


Figure 6.3.1

Translation: Unterschiede des erforderlichen Feuerwiderstandes = differences of the necessary fire resistance; Fläche = area.

The above-shown comparatively high percentile changes of the calculation results have to be relativated finally and have to be placed in relation to the finally interesting fire resistance times in minutes. With this, a differentiation according to single compartment areas proves to be interesting, as it is shown in the following Figures 6.3.2 to 6.3.6.

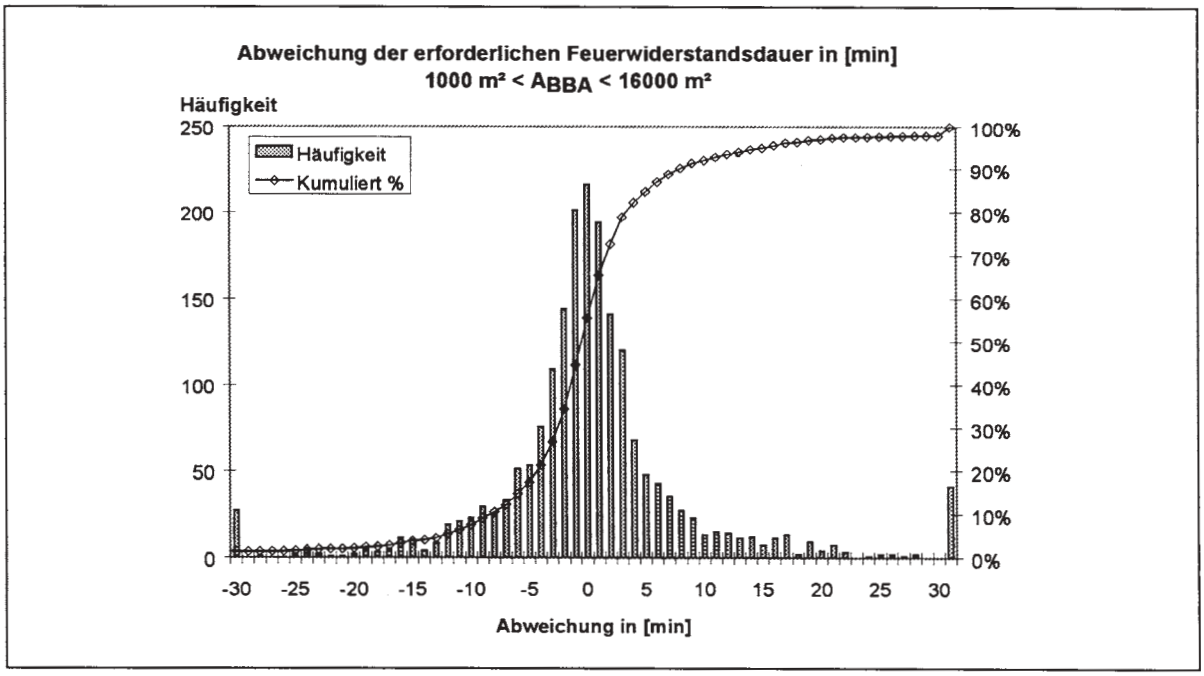


Figure 6.3.2

Translation: Abweichung der erforderlichen Feuerwiderstandsdauer = deviation of the necessary fire resistance duration; Häufigkeit = frequency; kumuliert = cumulated; Abweichung = deviation.

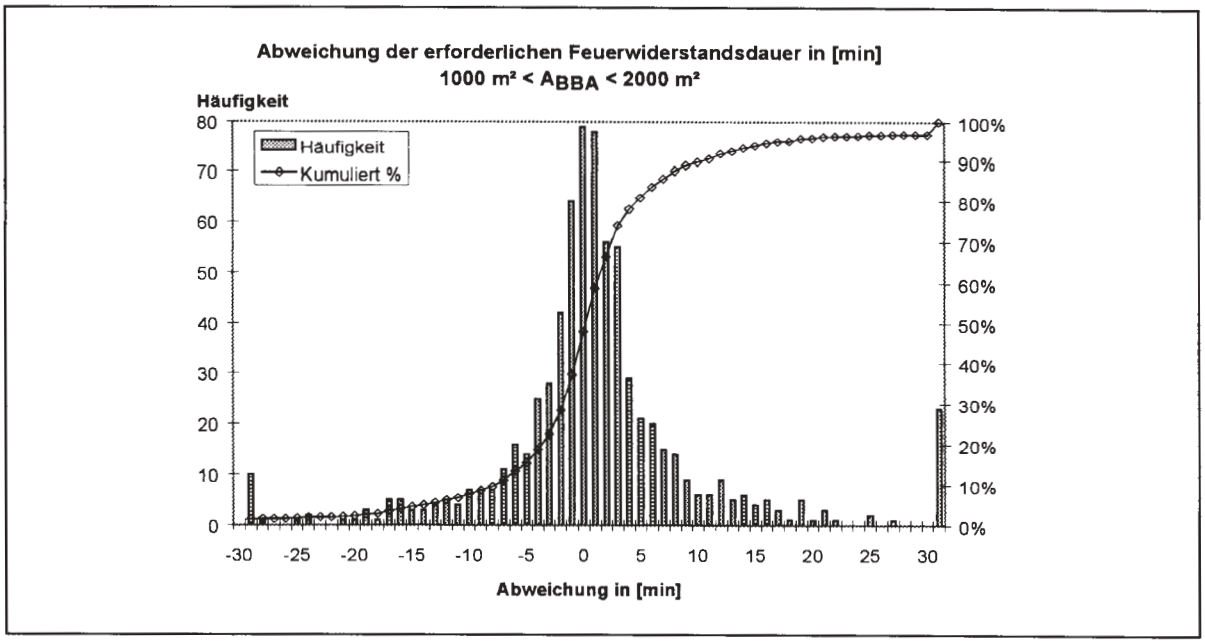


Figure 6.3.3

Translation: Abweichung der erforderlichen Feuerwiderstandsdauer = deviation of the necessary fire resistance duration; Häufigkeit = frequency; kumuliert = cumulated; Abweichung = deviation.

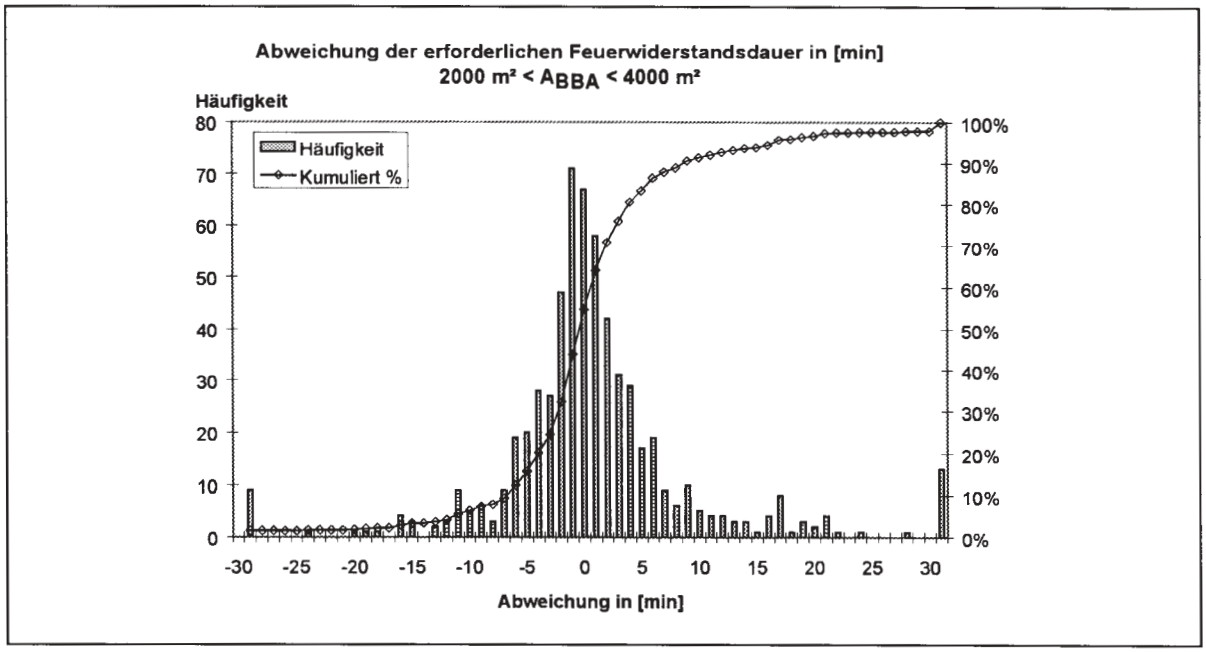


Figure 6.3.4

Translation: Abweichung der erforderlichen Feuerwiderstandsdauer = deviation of the necessary fire resistance duration; Häufigkeit = frequency; kumuliert = cumulated; Abweichung = deviation.

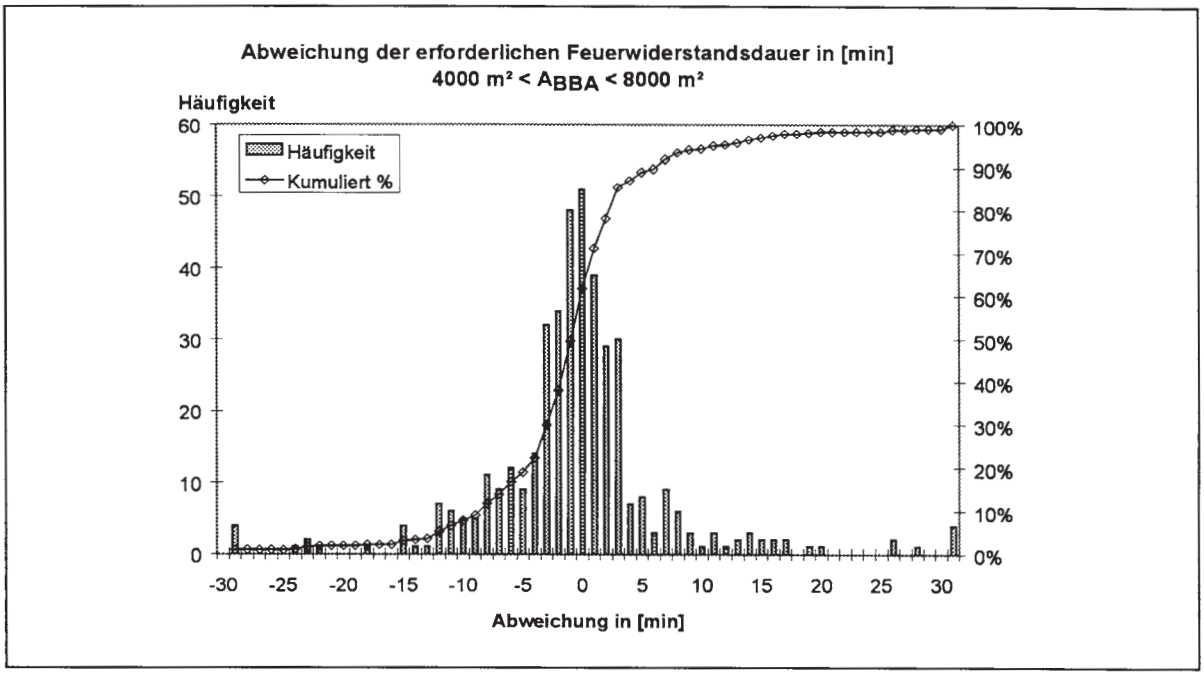


Figure 6.3.5

Translation: Abweichung der erforderlichen Feuerwiderstandsdauer = deviation of the necessary fire resistance duration; Häufigkeit = frequency; kumuliert = cumulated; Abweichung = deviation.

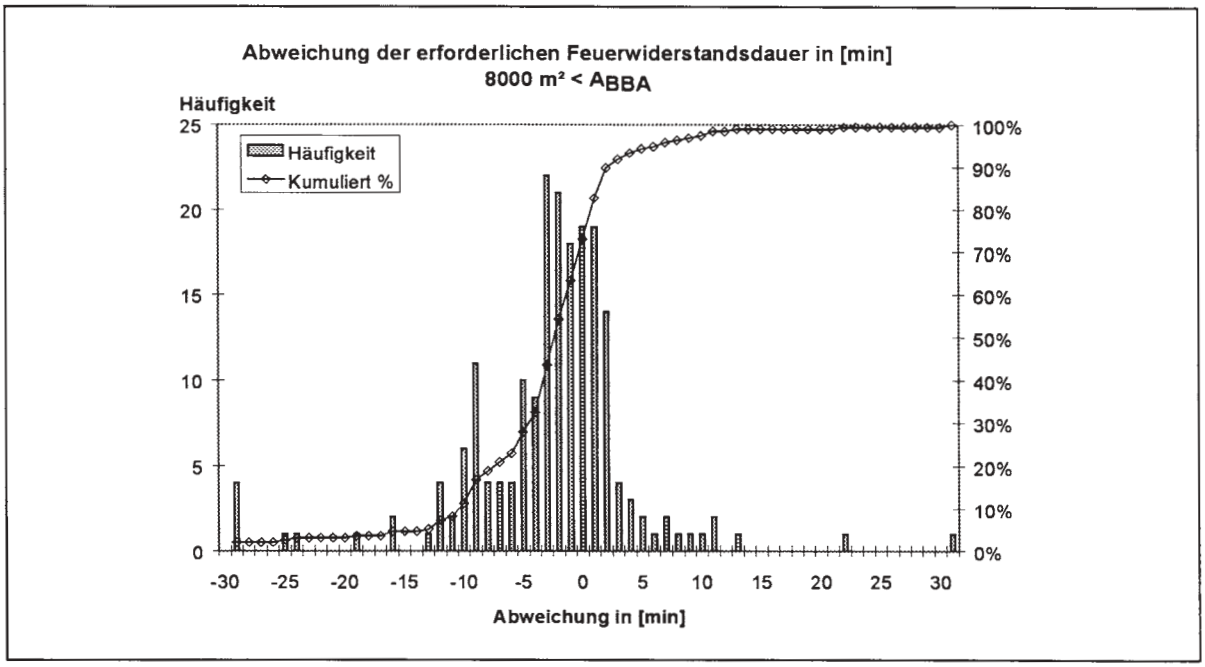


Figure 6.3.6

Translation: Abweichung der erforderlichen Feuerwiderstandsdauer = deviation of the necessary fire resistance duration; Häufigkeit = frequency; kumuliert = cumulated; Abweichung = deviation.

The curve-like gaussian distribution of the frequency in the deviation of the erf tF confirms a "compensating justice" in the sense of the average of calculations according to the old norm version, just as according to the version of 1998, and leads to similar results.
The following, in tabular form combined essential values show, that one has to expect, according to the trend, for greater fire fighting compartment areas somewhat smaller calculation results, whereas smaller fire compartment areas may show, with this, a certain intensification.

figure	area	50 %	15 %	85 %
6.3.2	all	- 0,5 minutes	- 6 minutes	+ 5 minutes
6.3.3	1.000 – 2.000 m^2	± 0 minutes	- 0,6 minutes	+ 7 minutes
6.3.4	2.000 – 4.000 m^2	- 0,5 minutes	- 5,5 minutes	+ 5,5 minutes
6.3.5	4.000 – 8.000 m^2	-1 minutes	- 6,5 minutes	+ 3 minutes
6.3.6	8.000 – 16.000 m^2	-2,5 minutes	- 9,5 minutes	+ 1,5 minutes

7 NORMATIVE CONSIDERATION OF OPENINGS

The calculated rate of the openings has a great influence on the result of the calculation according to all time equivalent methods. With this, one has to note for the practical use, that the openings are only available "steadily open" in the most seldom cases; rather, they are closed as glazing, doors, etc. firstly and will be activated as opening, or not, not before a case of fire. For this reason, a great importance is due to an applicable model-like representation of this opening characterization.

Normative definitions regarding this question are incorporated with the new version of the DIN 18230. They define the possibility of charging regarding the kind of opening seal. In the following, a summary is given in the quoted table D.3 of the norm.

line	kind of opening seal	possibility of charging
1	steadily open	always
2	to be opened from outside	always
3	self-opening seals	always
4	single window-glass	always
5	glazings with synthetic materials with a melting temperature < 300°C	in the roof and in the upper half of the wall always, in the lower half of the wall if $t_{ä} \geq 15$ min
6	double-window pane insulating glass	if $t_{ä} < 15$ min with 35%*) if $15 \leq t_{ä} \leq 30$ min with 50%*) if $t_{ä} > 30$ min with 100%
7	materials, which are demonstrable destroyed in fire according to standard temperature curve if $t_{ä} > 15$ min	if $t_{ä} > 15$ min with 100%, otherwise not
8	fire protection glazing	never
9	action-hindering glazing	never
10	wire reinforced glass with crosswise wires	never
*) If there is a factory fire brigade, the value may be doubled.		

Table D.3: Possibility of considering of openings in calculating the w-factor

As it is clearly recognizable, the table distinguishes two extreme values, namely in line 1 - 4 openings, that may be considered always, respectively in line 8 - 10 openings, that may be never considered.

The possibility of considering of the other kinds is made dependent on the determined time equivalent as a consequence. This means, according to the instructions of the norm, for the practical calculation, that, firstly, the openings of the kind of line 5 - 7 are not considered in the first step of iteration and, then, the settlement in dependence on this extension follows or not. A further step of iteration is not given explicitly.

The following explanations have to be noted regarding the single regulations:

All synthetic elements, that may be melt out, are summarized in line 5, for example Polycarbonate, PMMA and other elements, that are mostly fixed in rows of windows. Essentially, the dependence on the kind of opening (roof respectively upper half of the wall or lower half of the wall) is decisive for the possibility of charging.

According to line 6, double-window pane insulating glass is rated in dependence on the time equivalent of the first iteration with an opening percentage.

At the moment, materials according to line 7 do not exist with the appropriate proofs, since no test procedures are normated for this in Germany.

The assigned doubling of the stated values in the footnote, if there is a factory fire brigade, is proved by the fact, that a factory fire brigade will, should the occasion arise, create further openings by the use of power (destruction of window-panes), which may not be assumed for the action of a public fire brigade generally.

8 CONCLUSIONS

It has to be pointed out that this report is in fact provided because the work has been done in the scope of the research but the "Equivalent Time Methods" do not belong to the Natural Fire Safety Method developed and finally proposed here (see main part).

These "Equivalent Time Methods" have been analysed at the beginning of the research because, at this time, it was the only existing methods considering the ventilation conditions and the fire loads. However the weak point is that these methods refer to the ISO-Curve and do not depend on the structure type (protected steel, unprotected steel, reinforced concrete).

Despite the numerous numbers of available methods, only two different procedures exist in fact:

- New-Zealand method (it is an updated Petterson's version of the method)
- Annexe E of ENV 1991-2-2 (it is in fact the DIN 18230 – version 94)

The comparison between the results of the last method and the similar results deduced from the test database (see WG1 report) attest that the Annex E of EC1 part 2.2 gives very good results in case of protected steel structures. For unprotected steel structures the method is less efficient but seems to give reasonable results. These conclusions are of course limited to the conditions covered by the database and to the steel profile used in the comparison.

The Equivalent Time Method defined in ENV 1991-2-2 is a simplified method which may be used in a first approach. However it has to be kept in mind that, mainly for the unprotected steel structure, the results have to be checked by the full NFSC method described in the main report.

Moreover the equivalent time based on a unique temperature equivalence is not valid anymore for composite construction.

ANNEX1 : Comparative summary of the "TE" methods

Method/procedure	LAW M.
Author	LAW M.
When was it devised ?	1971
Basic Literature	*Law M.:"A Relationship Between Fire Grading and Building Design and Contents", Fire Research Station Note No. 877, 1971* "An Introduction to Fire Dynamics. The Post-flashover Compartment Fire"; Dougal Drysdale. (NFSC92) "Draft code of practice for the application of Fire Safety Engineering. Principles to Fire Safety in Buildings". BSi Standards. Panel FSM/-/5 - and Technical Commitee FSM/24 - Document 94/340340. 8th. of June 1994. (NFSC65) "Natural Fires in Large Scale Compartments"; BST, FRS, B.R. Kirby. June 1994 (NFSC40) "On the Equivalent Fire Exposure", Harmathy, Fire and Materials, Vol. 11, pages 95-104 (1987). (NFSC90) "Fire Safety in Constructional Steelwork", WG3 meeting of the 10th of August 95 in Paris (NFSC80) "Design Manual on the European Recommandations for the fire Safety of Steel Structures"; 1st Edition; ECCS - TC3 - Fire Safety of Steel Structures N°35; 1985. (NFSC91)
Experimental support Evaluated fire tests	TESTS (about 50 tests by different laboratories) (see pages enclosed = p26/27 of NFSC 91 and page II.36 of NFSC 80) Method established for a Maximum steel temperature of about 500°C.
Area of application and limits	Only for insulated steel (see page 338 of NFSC92 and page 105 of NFSC 65)
Main formulae	$t_e = k \frac{L}{(A_w A_t)^{\frac{1}{2}}}$ [min] L = Total Fire Load (kg of Wood) A_v = area of ventilation (m^2) A_t = area of walls and roof but not including openings (m^2) (! floor not included) k = a constant, usually taken as unity for large scale experimental fires (min m^2/kg)
How are the following influences allowed for ?	
-Thermal properties of the enclosure	No influence
- Fire load; relative to the area or the total surface area.	L = fire load (kg of Wood) = Total Fire Load
- Nature of the object on fire.	Solid Combustible (No flammable liquid fires) (see page 339 of NFSC92)
- Burning behaviour of the object in fire.	/
- Openings; different treatment vertical and horizontal ?	No
- Definition of the opening factor.	$(A_w A_t)^{-1/2}$
- Differentiating between ventilation controlled and fire-load controlled.	No (Tests corresponding to ventilation and fire-load controlled fire)

Comparative summary of the "TE" methods

Method/procedure	Petterson O. (Simplified approach)
Author	Petterson O. (Simplified approach)
When was it devised ?	
Basic Literature	Petterson O.: 'The Connection Between a Real Fire Exposure and the Heating Conditions According to Standard Fire Resistance Tests', European Convention for Constructional Steelwork, Chapter II, CECM-III-74-2E. (NFSC80) Petterson O., S.E. Magnusson and J. Thor, 'Fire Engineering Design of Steel Structures', Swedish Institute of Steel Construction, Publication No. 50, 1976. (NFSC45) "Fire Safety in Constructional Steelwork", WG3 meeting of the 10th of August 95 in Paris (NFSC80) "Design Manual on the European Recommandations for the fire Safety of Steel Structures"; 1st Edition; ECCS - TC3 - Fire Safety of Steel Structures N°35; 1985. (NFSC91) **"A Conceptual Approach Towards a Probability Based Design Guide on Structural Fire Safety"-CIB W14 Workshop "Structural Fire Safety" January 1983 NFSC 27**
Experimental support Evaluated fire tests	Based on Calculation results (One Zone Model) and a Maximum Steel Temperature of about 500°C (p. II.38 of NFSC 80)
Area of application and limits	.)For Insulated Steel and an Opening Factor ≥ 0.05 according to p.II.41 and II.43 of NFSC 80 .)Equation valid for unprotected steel, protected steel and simply supported reinforced concrete beams according to p.34 of NFSC 27
Main formulae	$t_e = 0.067\sqrt{k_f}\left(\frac{A_w\sqrt{h_w}}{A_t}f_k\right)^{-\frac{1}{2}} \bullet q_t$ q_t = fire load density (MJ/m^2 of total boundary surfaces) A_w = area of ventilation (m^2) h_w = weighted mean ventilation height (m) A_t = area of total boundary surfaces including the openings f_k = correction factor in case of horizontal openings
How are the following influences allowed for ?	
-Thermal properties of the enclosure	k_f takes into account of the thermal properties of the compartment $0.5 \le k_f \le 3$ (see page 148 enclosed of NFSC45)
- Fire load; relative to the area or the total surface area.	q_t = fire load density (MJ/m^2 of total boundary surfaces)
- Nature of the object on fire.	/
- Burning behaviour of the object in fire.	/
- Openings; different treatment vertical and horizontal ?	Yes see pages 56 and 57 enclosed of NFSC45
- Definition of the opening factor.	$\sqrt{\frac{A_w\sqrt{h_w}}{A_t}}$
- Differentiating between ventilation controlled and fire-load controlled.	Ventilation Controlled (but on the safe side for fire-load control: see p.II.17 of NFSC 80)

Comparative summary of the "TE" methods

Method/procedure	Petterson O. (Global approach)
Author	Petterson O. (Global approach)
When was it devised ?	1976
Basic Literature	Petterson O.: 'The Connection Between a Real Fire Exposure and the Heating Conditions According to Standard Fire Resistance Tests', European Convention for Constructional Steelwork, Chapter II, CECM-III-74-2E. (NFSC80) Petterson O., S.E. Magnusson and J. Thor, 'Fire Engineering Design of Steel Structures', Swedish Institute of Steel Construction, Publication No. 50, 1976. (NFSC45) "Fire Safety in Constructional Steelwork", WG3 meeting of the 10th of August 95 in Paris (NFSC80) "Design Manual on the European Recommandations for the fire Safety of Steel Structures"; 1st Edition; ECCS - TC3 - Fire Safety of Steel Structures N°35; 1985. (NFSC91)
Experimental support **Evaluated fire tests**	Based on Calculation results (One Zone Model)
Area of application and limits	Steel (Protected and Unprotected)
Main formulae	See tables giving t_e as a function of q_t, $A.h^{1/2}/A_t$, F/V, λ, d. q_t = fire load density (MJ/m^2 of total boundary surfaces) A_w = area of ventilation (m^2) h_w = weighted mean ventilation height (m) A_t = area of total boundary surfaces including the openings
How are the following influences allowed for ?	
- Thermal properties of the enclosure	k_f takes into account of the thermal properties of the compartment $0.5 \leq k_f \leq 3$ (see page 148 enclosed of NFSC45)
- Fire load; relative to the area or the total surface area.	q_t = fire load density (MJ/m^2 of total boundary surfaces) /
- Nature of the object on fire.	/
- Burning behaviour of the object in fire.	
- Openings; different treatment vertical and horizontal ?	Yes see pages 56 and 57 enclosed of NFSC45
- Definition of the opening factor.	$\sqrt{\frac{A_w\sqrt{h_w}}{A_t}}$
- Differentiating between ventilation controlled and fire-load controlled.	Ventilation Controlled (but on the safe side for fire-load control: see p.II.17 of NFSC 80)

Comparative summary of the "TE" methods

Method/procedure	CIB W14
Author	CIB W14
When was it devised ?	
Basic Literature	CIB W14 Workshop Report, 'Design Guide: Structural Fire Safety', Fire Safety Journal, Vol. 10, No. 1 (1986), pp 77-154.
Experimental support **Evaluated fire tests**	
Area of application and limits	
Main formulae	$t_c = q_f \cdot c \cdot w$ $w = w' \left(\frac{A_f}{A_w}\right)^{\frac{1}{2}}$ and $w' = \left(\frac{A_f}{A_t \sqrt{h}}\right)$
How are the following influences allowed for ? - Thermal properties of the enclosure - Fire load; relative to the area or the total surface area. - Nature of the object on fire. - Burning behaviour of the object in fire. - Openings; different treatment vertical and horizontal ? - Definition of the opening factor. - Differentiating between ventilation controlled and fire-load controlled.	= Petterson's simplified method

Comparative summary of the TE methods

Method/procedure	Harmathy T.Z.
Author	Harmathy T.Z.
When was it devised ?	1987
Basic Literature	Harmathy T.Z.: 'On the Equivalent Fire Exposure', Fire and Materials, Vol. 11 (1987), pages 95-104. (NFSC 90)
Experimental support Evaluated fire tests	Theoretical method validated by some experimental tests.
Area of application and limits	This method cannot be applied to compartment boundaries containing important load-bearing components in, or in the immediate vicinity of, the enclosure surface. For example, it cannot be applied to enclosures built with unprotected steel.
Main formulae	$t_c = 0.11 + 0.16 \cdot 10^{-4} H' + 0.13 \cdot 10^{-9} (H')^2 \text{(hour)}$ $H' = \dfrac{10^6 (11.0\delta + 1.6) A_f L}{(A_t - A_v) \cdot (\lambda \rho c_p)^{\frac{1}{2}} + 935 (\Phi A_f L)^{\frac{1}{2}}}$ where $\delta = 0.79 (h_c^3 / \Phi)^{\frac{1}{2}} \leq 1$ Φ = ventilation parameter $= \rho_a A_v (g h_v)^{\frac{1}{2}}$ (kg/s) ρ_a = density of air entering the compartment (kg/m^3) g = gravitational constant (m/s^2) A_v = area of ventilation (m^2) L = fire load
How are the following influences allowed for ?	
- Exterior components	$(\rho\lambda c)^{1/2}$; h_c
- Fire load; relative to the area or the total surface area.	-relative to floor area.
- Nature of the object on fire.	for cellulosic fires:
- Burning behaviour of the object in fire.	/
- Openings; different treatment vertical and horizontal ?	-No
- Definition of the opening factor.	/
- Differentiating between ventilation controlled and fire-load controlled.	-No

Natural Fire Safety Concept WG 2 : Equivalent Time Methods

Comparative Summary

Method	DIN V 18230 (sept. 1987)
Author	
When was it devised ?	mentioned for the first time in DIN V 18230 (edition 1968)
Basic literature	- Bub, H. Grundlagen zur Festlegung von Sicherheitsanforderungen im konstruktiven baulichen Brandschutz, Bundesbaublatt 10/1978. - Knublauch, E. Einführung in den baulichen Brandschutz, Düsseldorf 1978. - Bub, H. Baulicher Brandschutz im Industriebau, Köln 1979. - Schubert, K.-H., Hosser, D. Zulässige Brandabschnittsgrößen im Industriebau nach E DIN 18230, Bauphysik 1980. - Industriebaurichtlinie - Ind Bau R - , 1985. - Falke, J., Halfkann, K.-H. Brandschutz nach Maß im Industriebau, DSTV Köln 1989.
Experimental support Evaluated fire tests	⇨ combustion factor m (Abbrandfaktor m) Beiblatt 1 zu DIN 18230 - Ueberall, T. Bewertung von Brandlasten in größeren Räumen, Forschungsbericht MPA Dortmund 1990.
Area of application	industrial buildings $A \leq 30000\ m^2$ (– Ind Bau R)
Main equations	$q_R = \frac{\Sigma\ (M_i \cdot H_{ui} \cdot m_i \cdot \psi_i)}{A_\epsilon}$ $t_e = q_R \cdot c \cdot w$ $erf\ t_F = t_e \cdot \gamma \cdot \gamma_{n,b}$
How are the following influences considered ? - Exterior components - Fire load - Object on fire • burning behaviour - Openings • different treatment vertical and horizontal ? • definition of opening factor • Differentiating between ventilation controlled and fire-load controlled	**Factor c** - fire load q_R relative to the floor area A - evalutaion of actual burning material according to its combustibility by Beiblatt 1 DIN 18230 – combustion factor m, calorific value H_u ⇨ reference case : temperature development of steel plate (t=15 cm) under 5 cm concrete. - ventilation factor w in relation to the ($A_{v,h}$ / A) - ratio and a general differentiation concerning the position of the openings $A_{v,h} = A_v + k_f \cdot A_h$ - fire-load controlled

Natural Fire Safety Concept WG 2 : Equivalent Time Methods

Comparative Summary

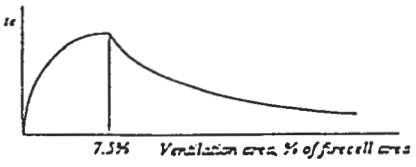
Method	E DIN 18230 (july 1994)
Author	
When was it devised ?	1994
Basic literature	- Schneider, U. Überprüfung der Faktoren m und w in DIN 18230, Tagungsband Seminar "Brandschutz in Forschung und Praxis", TU Braunschweig 1988. - Kersken-Bradley, M., Max, U., Schneider, U. Neuberechnung der Wärmeabzugsfaktoren w für DIN 18230 Teil 1, Arbeitsgemeinschaft Brandsicherheit Kassel 1990.
Experimental support Evaluated fire tests	⇨ combustion factor m (Abbrandfaktor m) Beiblatt 1 zu DIN 18230 - Ueberall, T. Bewertung von Brandlasten in größeren Räumen, Forschungsbericht MPA Dortmund 1990.
Area of application	industrial buildings
Main equations	$q_R = \frac{\Sigma\ (M_i \cdot H_{ui} \cdot m_i \cdot \psi_i)}{A}$ $t_e = q_R \cdot c \cdot w$ $erf\ t_F = t_e \cdot \gamma \cdot a_L$
How are the following influences considered ? - Exterior components - Fire load - Object on fire • burning behaviour - Openings • different treatment vertical and horizontal ? • definition of opening factor • Differentiating between ventilation controlled and fire-load controlled	**Factor c** - fire load q_R relative to the floor area A - evalutaion of actual burning material according to its combustibility by Beiblatt 1 DIN 18230 – combustion factor m, calorific value H_u ⇨ reference case : temperature development of steel plate (t=15 cm) under 5 cm concrete. - Consideration of vertical and horizontal openings by w_0 (⇨ Fig.2) influence of height of compartment by a_w (⇨ Fig.3) $w = w_0 \cdot a_w$ - fire-load controlled

Natural Fire Safety Concept WG 2 : Equivalent Time Methods

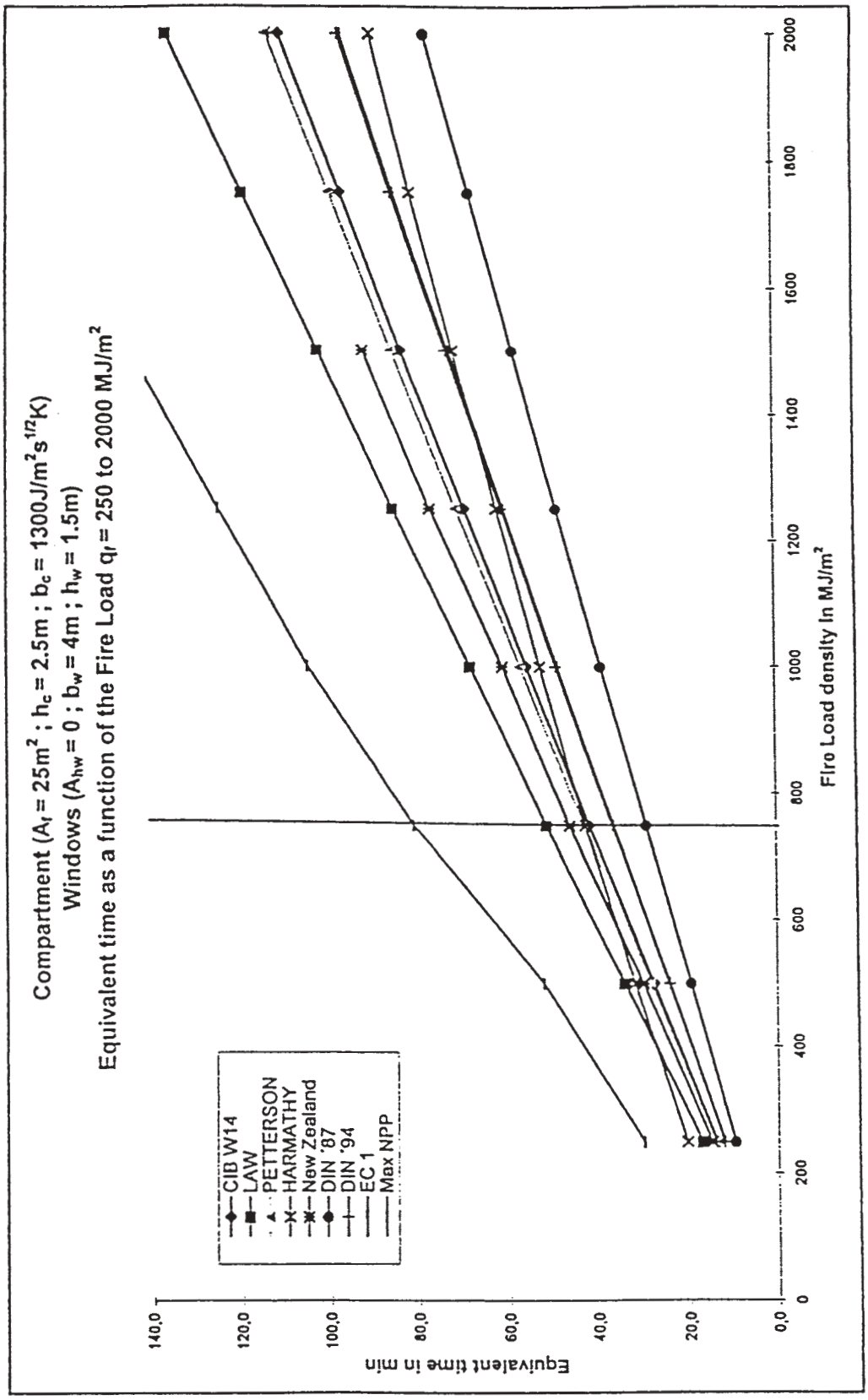
Comparative Summary

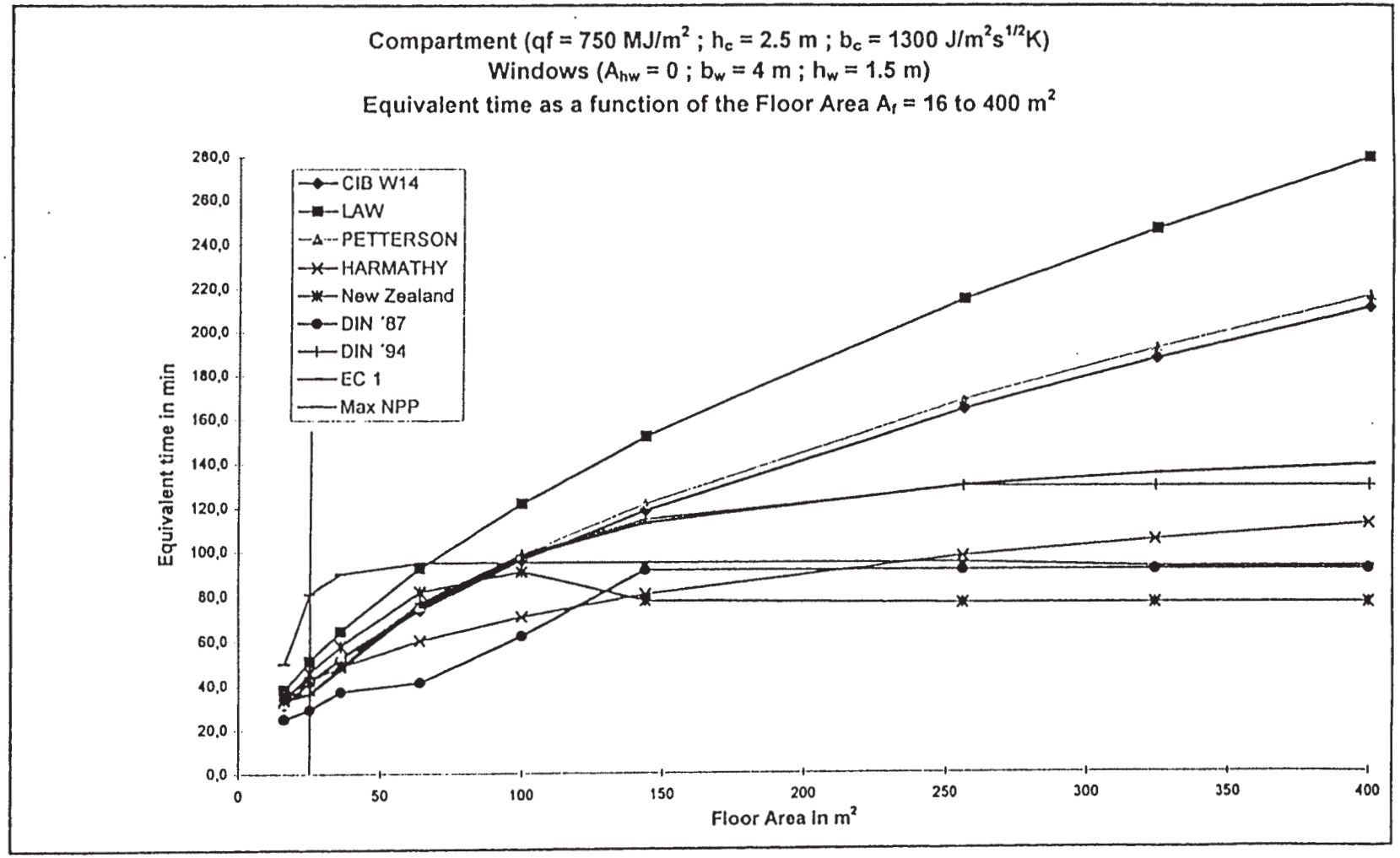
Method	EC 1 Part 2-2 Annex E (11/94)
Author	
When was it devised ?	1994
Basic literature	
Experimental support Evaluated fire tests	
Area of application	
Main equations	$q_d = \gamma_q \cdot \gamma_n \cdot q_k$ ⇨ Annex D $t_{e,d} = q_{f,d} \cdot k_b \cdot w_f$
How are the following influences considered ? - Exterior components - Fire load - Object on fire • burning behaviour - Openings • different treatment vertical and horizontal ? • definition of opening factor • Differentiating between ventilation controlled and fire-load controlled	**Factor c** - fire load $q_{f,d}$ relative to the floor area A_f - evalutaion of actual burning material according to its combustibility by Annex D – combustion factor m, calorific value H_u - calculation of ventilation factor w_f in relation to the ratios of the vertical, resp. horizontal opening area to the floor area (⇨ α_v , α_h) and the height H of the compartment $b_v = 12.5\ (1 + 10\ \alpha_v - \alpha_v^2)$ $w_f = \left(\frac{6}{H}\right)^{0.3} \cdot (0.62 + 90\ (0.4 - \alpha_v)^4 / (1 + b_v \alpha_h)) \geq 0.5$ - fire-load controlled

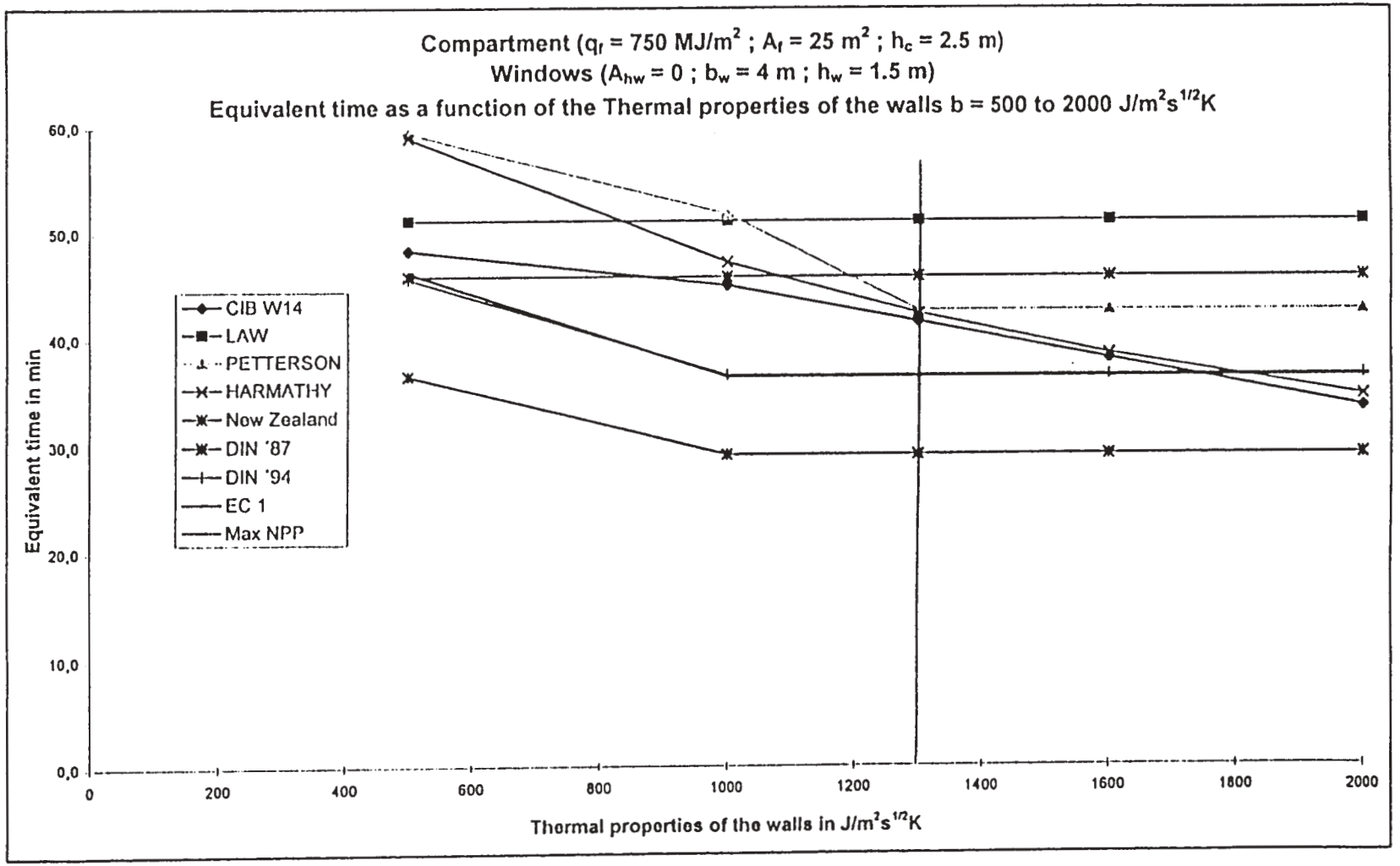
Comparative summary of the TE methods

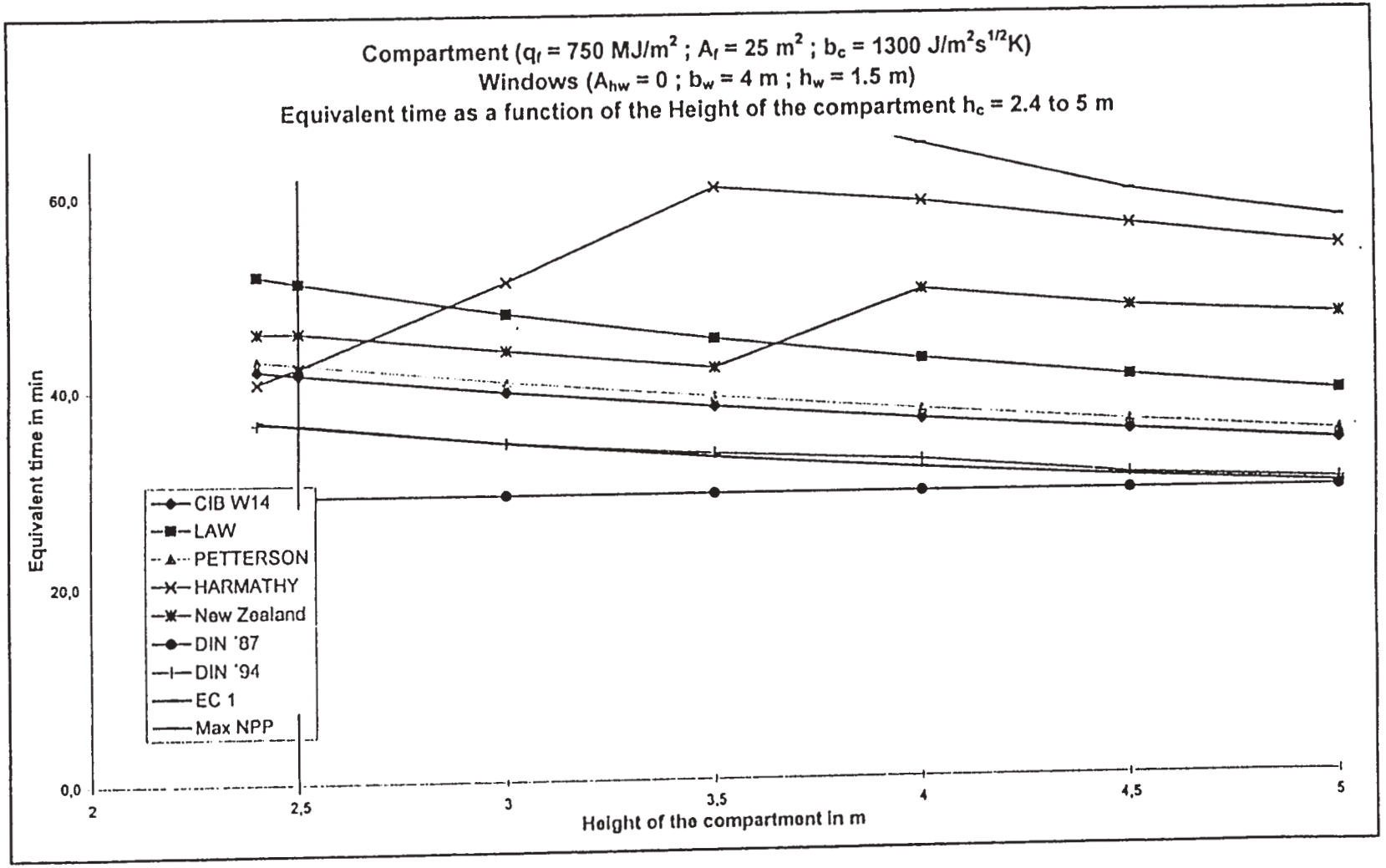
Method	New Zealand Method 1
Author	G.C. Clifton. Hera Structural Engineer
When it was Devised	Amended 18/05/93
Basic Literature	- Based in M. Law formulae. - Lawson R.M. and Newman G.M. "Fire Resistant Design of Steel Structures"; The Steel Construction Institute, Ascot, England, 1990. - Buchanan A.H. And King-Turner S; Equivalent Fire Severity; Private Report Prepared by Dr Buchanan, University of Canterbury, Chirstchurch, New Zealand, 1993. - Drysdale . An Introduction to Fire Dynamics; John Wiley and sons, New york, 1993. - Babrauskas v. and Williamson R.B.; Post -Flashover Compartment Fires; Basis of a theoretical Model; Fire and Materials, Volume 2 No. 2, 1978.
Experimental Support Evaluated Fire Test	- Thomas I.R. et. al. Fire in Offices; BHP Structural Steel Development Group, Melbourne, Australia, 1990. - Thomas I.R. et. al. Fire Test on the 140 Willians street Office Building; BHP Co. Ltd. Melbourne Australia, 1993.
Area of application and limits	- Large and small compartment $A_{ef} \leq 150\ m^2$. - For FHC 4, $q_f > 1500\ MJ/m^2$. Fire engineering design. - Sprinklers required. - C_3=1.
Main formulae	If $A_v \geq 0.075 \cdot A_{ef}$ $S_c = C_1 \cdot C_2 \cdot C_3 \cdot C_4 \cdot \omega \cdot qf$, (1) $\omega = \frac{A_{ef}}{A_{ef}\left(A_v \frac{\sqrt{h_v}}{A_{ef}}\right)^{0.5}}$ (2) If $A_v < 0.075 \cdot a_{ef}$ $S_c = C_2 \cdot C_3 \cdot C_4 \cdot \left[0.0267 \cdot (S_{C75} 100 \frac{A_v}{A_{ef}}) - 0.0018 \cdot (S_{C75}(100 \frac{A_v}{A_{ef}})^2)\right]$ (3) S_{C75}= *The calculated value of Sc from equation* (1) *using* $A_v = 0.075 \cdot A_{ef}$
How are the following influences allowed for? - Exterior components -Fire load; relative to the area or the total surface area; -Nature behaviour of the object on fire; -Openings; different treatment vertical and horizontal? -Definition of opening factor. -Differentiating between ventilation controlled and fire-load controlled.	- Depending on bounding elements C_1 varies from C_1=0.067 to 0.11. - q_f = fire load (MJ/m^2) for the 150 m^2 floor area under consideration. Horizontal opening not taken into account. vertical openings Equation (2) Yes, equations (1) and (3)  7.5% *Ventilation area % of fire cell area*

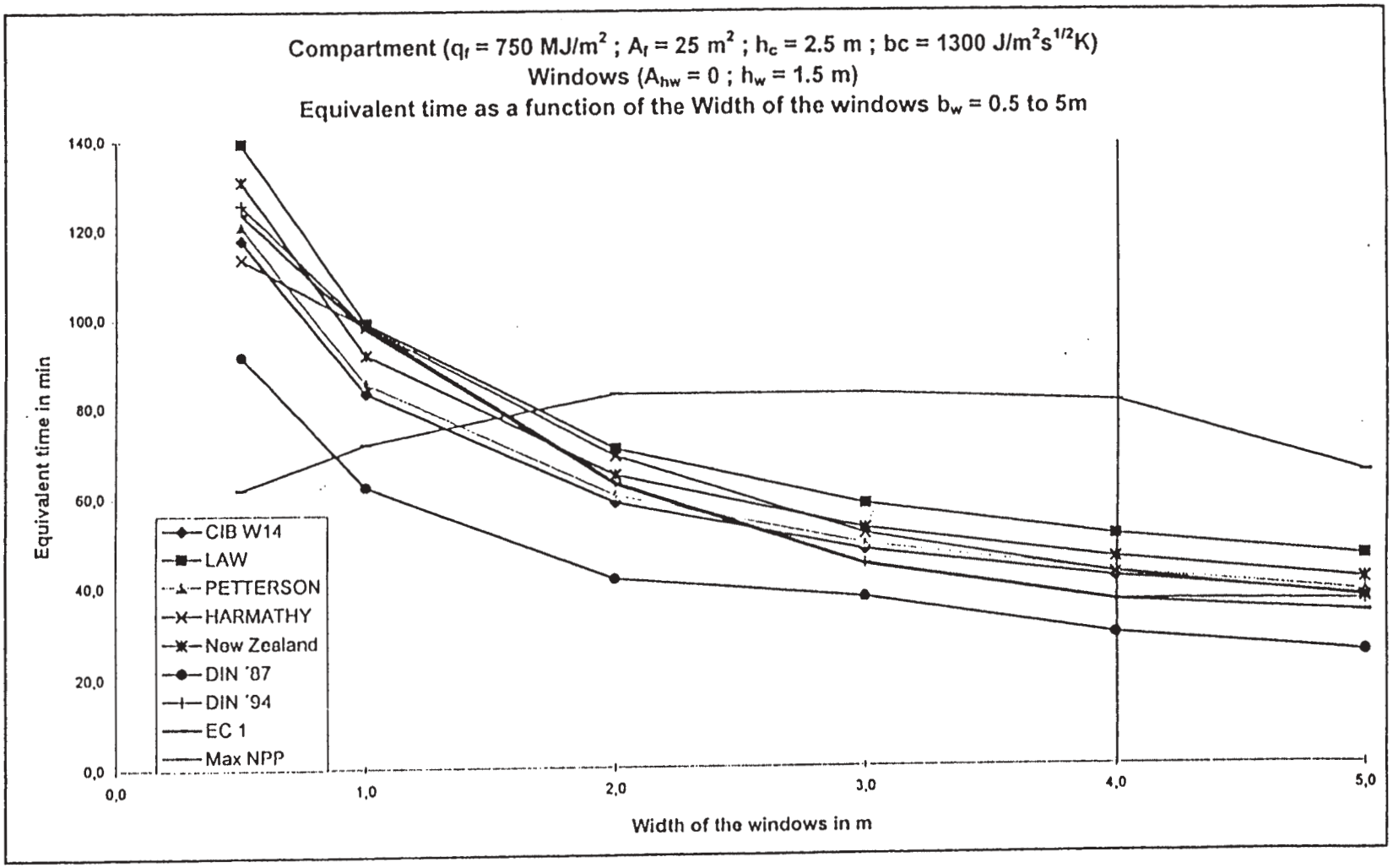
ANNEX 2 : Parameter sketch

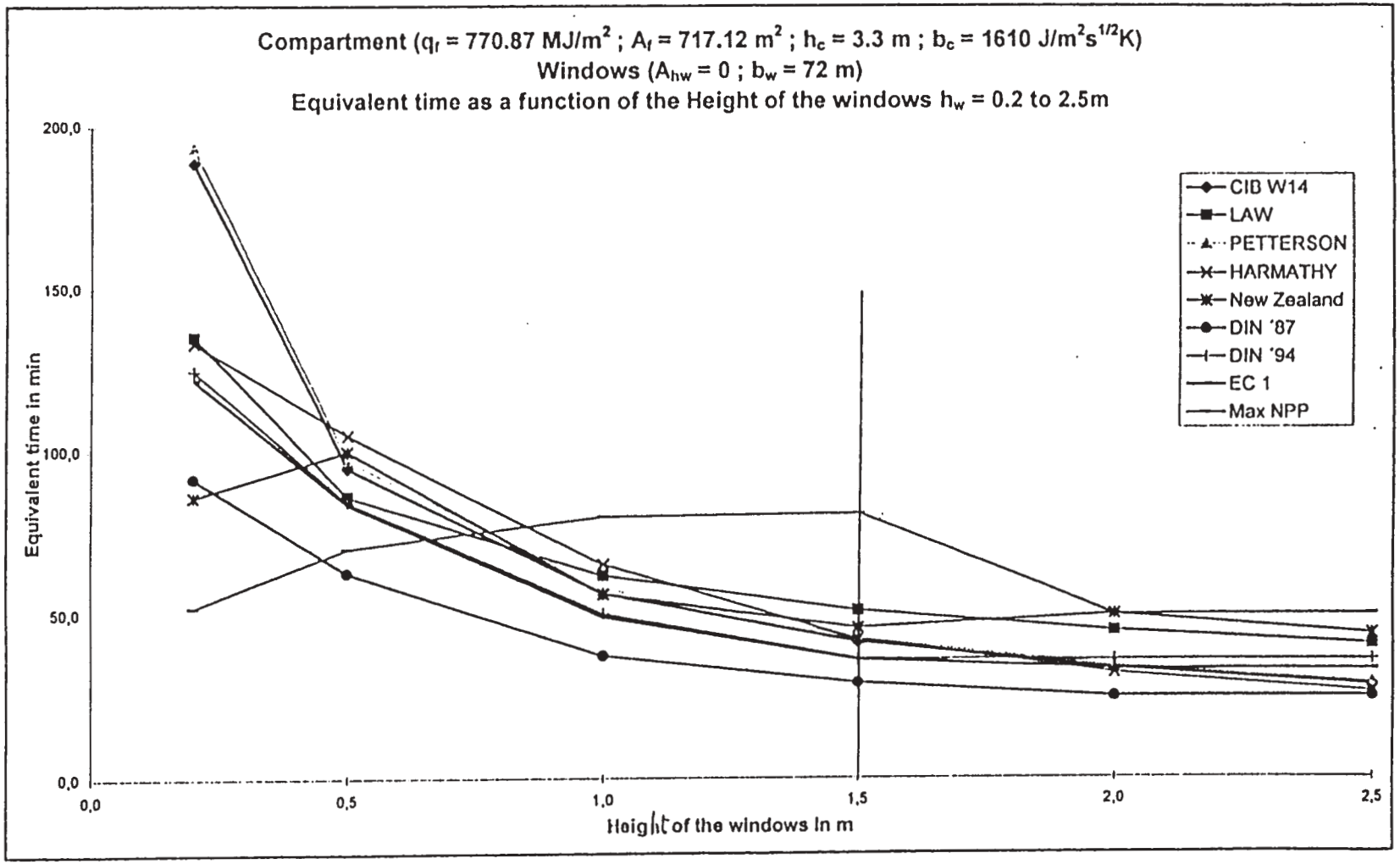



Compartment (qf = 750 MJ/m² ; hc = 2.5 m ; bc = 1300 J/m²s^1/2K)
Windows (Ahw = 0 ; bw = 4 m ; hw = 1.5 m)
Equivalent time as a function of the Floor Area Af = 16 to 400 m²
CIB W14
LAW
PETTERSON
HARMATHY
New Zealand
DIN '87
DIN '94
EC 1
Max NPP
Equivalent time in min
Floor Area in m²
0,0
20,0
40,0
60,0
80,0
100,0
120,0
140,0
160,0
180,0
200,0
220,0
240,0
260,0
280,0
0
50
100
150
200
250
300
350
400


Compartment (q_f = 750 MJ/m^2 ; A_f = 25 m^2 ; h_c = 2.5 m)
Windows (A_{hw} = 0 ; b_w = 4 m ; h_w = 1.5 m)
Equivalent time as a function of the Thermal properties of the walls b = 500 to 2000 J/m^{2}s$^{1/2}$K
Equivalent time in min
60,0
50,0
40,0
30,0
20,0
10,0
0,0
CIB W14
LAW
PETTERSON
HARMATHY
New Zealand
DIN '87
DIN '94
EC 1
Max NPP
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Thermal properties of the walls in J/m^{2}s$^{1/2}$K


Compartment (q_f = 750 MJ/m^2 ; A_f = 25 m^2 ; b_c = 1300 J/m^{2}s$^{1/2}$K)
Windows (A_{hw} = 0 ; b_w = 4 m ; h_w = 1.5 m)
Equivalent time as a function of the Height of the compartment h_c = 2.4 to 5 m
Equivalent time in min
60,0
40,0
20,0
0,0
2
2,5
3
3,5
4
4,5
5
Height of the compartment in m
CIB W14
LAW
PETTERSON
HARMATHY
New Zealand
DIN '87
DIN '94
EC 1
Max NPP


Compartment (q_f = 750 MJ/m^2 ; A_f = 25 m^2 ; h_c = 2.5 m ; bc = 1300 J/m^{2}s$^{1/2}$K)
Windows (A_{hw} = 0 ; h_w = 1.5 m)
Equivalent time as a function of the Width of the windows b_w = 0.5 to 5m
Equivalent time in min
140,0
120,0
100,0
80,0
60,0
40,0
20,0
0,0
0,0
1,0
2,0
3,0
4,0
5,0
Width of the windows in m
CIB W14
LAW
PETTERSON
HARMATHY
New Zealand
DIN '87
DIN '94
EC 1
Max NPP


Compartment (q_f = 770.87 MJ/m^2 ; A_f = 717.12 m^2 ; h_c = 3.3 m ; b_c = 1610 J/m^{2}s$^{1/2}$K)
Windows (A_{hw} = 0 ; b_w = 72 m)
Equivalent time as a function of the Height of the windows h_w = 0.2 to 2.5m
Equivalent time in min
200,0
150,0
100,0
50,0
0,0
0,0
0,5
1,0
1,5
2,0
2,5
Height of the windows in m
CIB W14
LAW
PETTERSON
HARMATHY
New Zealand
DIN '87
DIN '94
EC 1
Max NPP

III.2 WORKING GROUP 3

FIRE CHARACTERISTICS FOR USE IN A NATURAL FIRE DESIGN OF BUILDING STRUCTURES

1 INTRODUCTION

Traditionally, structural fire safety design is based on conventionally rather than on physically based thermal actions. This certainly holds for the international standards in the field. Therefore, the release of Eurocode 1, part 2-2: "Actions on structures exposed to fire", should be seen as a turning point. For the first time in international standardisation, the natural fire concept is presented as an - for the time being - informative option. This option opens the possibility for a more realistic and functionally based fire safety design, enabling to achieve rational and uniform safety levels.

In the Natural Fire Safety approach, parameters like the fire load, the rate of heat release and the heat loss to the walls and through openings can play an important role. With fire models, the temperature development in a compartment can be calculated as a function of the input data. At present, there is a large number of different fire models available, ranging in complexity from very simple to extremely complex. Each of these models needs its own set of input data; the simple models need little input where the advanced models need very detailed input data, resulting in much more detailed information of the conditions in the building during the anticipated fire.

The aim of the present report is to supply ready-to-use guidance on the input data for natural fire design of building structures to architects, designers and consultants who have no expert knowledge of fire modelling. The main goal is that the Natural Fire Safety Concept can be explored and used by all partners involved in building design and construction process.

The first step is to define the fire scenarios as explained in the next chapter.
In the third chapter, a global description is given of the various types of fire models, with for each model the necessary input data. In the chapters thereafter the main aspects of the Fire Characteristics (input data) are analysed: fire load density, fire size, fire shape and rate of heat release.

2 FIRE SCENARIO

2.1 CONCEPT*

The specification of appropriate design fire scenarios and design fires is a crucial aspect of fire safety design. The assumptions made with regard to these factors have major influence on all aspects of the design as they represent the input for most of the quantification processes.

A design fire scenario is the description of the course of the particular fire with respect to time and space. It includes the impact of the fire on building features, occupants, fire safety systems and all other factors. It would typically define the ignition source and process, the growth of fire on the first item ignited, the spread of fire, the interaction of the fire with its environment and its decay and extinction. It also includes the interaction of the fire with the building occupants and the interaction with the features of, and fire safety systems within the building.

In reality, the number of possible fire scenarios in most buildings approaches infinity. It would be impossible to analyse all scenarios even with the aid of the most sophisticated computing resources. This infinite set of possibilities needs to be reduced to a finite set of design fire scenarios that are amenable to analysis. Design fire scenarios for analysis should be based on the "credible worst case fire scenario". That is to say that more onerous fire scenarios have an acceptably low probability of occurring and that the consequence of those scenarios would need to be borne by society. It is desirable that regulatory authorities are involved in the selection of the design fire scenarios.

One of the main parameters of the design fire scenario is the design fire. A design fire is an idealisation of real fires that may occur in the building and represents a credible worst case of possible fires

This chapter is focused on the definition of the fire scenario relevant for the structural analysis. It has to be pointed out that many other fire scenarios, which do not influence the structural safety, have to be considered for other objectives. For instance, smouldering fires may have the potential to cause a large number of fatalities in certain occupancies such as residential buildings.

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* The text of this paragraphs has been extracted partially from the document "ISO/WD 13388 - Fire Safety Engineering - Design fire scenarios and design fires" [2-1].

2.2 FIRE SCENARIO DEFINITION

A fire scenario implies to define data concerning the fire itself (size and type of ignition source, distribution and type of fuel, fire load density, fire spread...), the data influencing the fire development (internal ventilation conditions, external environmental conditions, state of doors, breakage of windows, building air handling system, fire compartment size, fire compartment wall properties, influence of the active fire fighting measures...) and the position of the fire of which the choice depends on the structure (fire near a wind bracing system, fire involving several columns, fire affecting strongly loaded elements...)

All the above mentioned data have to be identified in a systematic manner for the whole building. For example, for the fire itself, a systematic review should be conducted to establish the potential fire hazards within the building. The review should take account of factors [2-2] such as:

(a) general layout;
(b) potential ignition sources;
(c) nature of the activities;
(d) anticipated occupancy;
(e) materials of construction;
(f) combustible contents;
(g) any unusual factors.

2.2.1 DESIGN FIRE

Figure 5-7 of chapter 5 enables to define a design fire by giving a rate of heat release as a function of:

- the fire growth rate measured by the parameter $t_\forall$
- the fire load density q_f
- the fire area A_{fi}
- the ventilation conditions

In a specific cases like exhibition halls, air terminal halls, the fire area A_{fi} can be easily defined by the layout of the combustible [2-3]. Otherwise the fire area A_{fi} is equal to the fire compartment area A_f.

The design fire will be used as input for the WG1 methods. If there is no flashover, two-zone programs combined with Hasemi's model [2-3] can be applied. Otherwise the post-flashover fire can be analysed with the program OZONE which considers the influence of the ventilation on the Rate of Heat Release.

The details are given in chapter 5.

2.3 COMPARTMENT

2.3.1 IDENTIFICATION

- The first step is to identify all the enclosures. An enclosure is surrounded by walls, ceiling and floor so that the smoke and the heat produced by the fire is kept inside the compartment, or will flow outside through openings, forced ventilation, windows or doors. For each enclosure, the boundaries will be evaluated by engineering judgement and a fire resistance time will be chosen (5', 10', 15', 20'...).
- The second step is to identify the requirements for fire compartments. According to 6.2.2.4, no spread of fire from one fire compartment to adjacent compartments shall be considered, if the boundaries satisfy the required ISO-ratings.
- In order to determine whether flashover will occur, the compartments with the worst combination of design rate of heat release (Figure 5-7), compartment geometry (area and height), ventilation conditions and enclosure wall properties will be considered. Usually, the smallest enclosures are relevant. In case of flashover, the worst case compartments depend on the same parameters. These compartments can be one enclosure, several adjacent enclosures or the whole fire compartment. In case of multiple enclosures the decay in the fire spread due to the walls will be considered.

2.3.2 VENTILATION CONDITIONS

In short the following assumptions will be considered:

- Glazing without an ISO-rating will be considered opened (broken) from the beginning of the fire. Only in specific cases of enclosures with very large windows, not all the glazing is assumed to be broken.
- Doors will be considered to be closed. (Note: If no other openings exist, the doors are assumed to be open)

2.3.3 INFLUENCE OF THE ACTIVE FIRE FIGHTING MEASURES

In case no flashover occurs, the active fire fighting measures will influence the choice of the area of the fire A_{fi}. In case of a fully engulfed fire, the value of the design fire load will be reduced by taking into account the effect of the fire fighting measures (see the work of the WG5).

2.3.4 POSITION OF THE FIRE

The worst situation regarding the importance of the structural elements, affected by the fire, will be considered.

2.4 CONCLUSION

Identification of the appropriate fire-scenarios is crucial to achieve a building design that fulfils the fire safety performance objectives. The choice of the design fire scenarios is the starting point of the natural fire safety concept.
This key assumption should be decided upon by mutual agreement with the Regulatory Authorities.

3 FIRE MODELLING

3.1 AVAILABLE TYPES OF FIRE MODELS

In order of increasing level of complexity, the following types of models are distinguished:

Nominal Fire Curves
The development in time of the uniform gas temperature in a fire compartment is set by convention, i.e. no physical parameters are taken into account. In some models of this kind, the fire duration is related to the fire load density. In addition, a differentiation is made with respect to the type of combustible materials (e.g. cellulose vs. hydrocarbon). These models are describing the post flashover fires; from the start the compartment is assumed to be involved in the fire, discarding the growth phase of the fire.

Parametric Fire Curves
These are fire models in which the development in time of the uniform gas temperature in a fire compartment depends on a number of physical parameters. These models assume also post flashover conditions. From the start of the fire, the whole fire compartment is assumed to be involved in the fire. These models require global input data about the fire load density (chapter 4), the size of the openings in the compartment (chapter 6), and the thermal properties of the boundaries of the compartment (chapter 7).

One Zone Models
In One Zone Models, the temperature in the fire compartment is uniform. Gas temperature development is calculated by solving the heat and mass balance for the system consisting of the fire compartment with its boundary structure including ventilation openings. Necessary input data: the amount of combustible materials (chapter 4), the rate of heat release (chapter 5), the ventilation conditions (chapter 6) and the thermal properties of structural elements bounding the fire compartment (chapter 7).

Multi-Zone Models
These models are used when the fire is localised. The fire compartment is divided into a hot zone, with a uniform temperature, above a fresh air zone and a fire plume, which feeds the hot zone just above the fire. For each of the zones, the heat and mass balance is solved. (Semi-) empirical relations govern plume entrainment, radiative heat exchange between zones, and mass flow through openings to adjoining compartments [3-3]. Beside the input data necessary for one zone models, the (growth of the) fire should be known. Only some of the available models can handle oxygen-starved conditions.

Field models (CFD)
C(omputational) F(luid) D(ynamics) Models are based on two- or three-dimensional heat and mass transport, solving the equations of conservation of mass, momentum and energy for discrete points in the enclosed compartment and are, therefore, commonly referred to as "field models". Input data are the same as for the multi zone models, however a more nuanced approach is viable. E.g., material properties and boundary conditions may be defined as function of the temperature, if necessary. Sub models are available for modelling the combustion and radiation. Field models enable the engineer to consider complex geometries.

3.2 INPUT DATA

Of the various fire models reviewed in the above section, only the Nominal Temperature-Time Curves and the parametric curves are recognised in Eurocode 1, part 2-2.

Three types of Nominal Fire Curves are specified: the ISO standard curve, the hydrocarbon curve and a curve representative for external fire exposure.
See Figure 3-1. None of these curves requires physical input data.

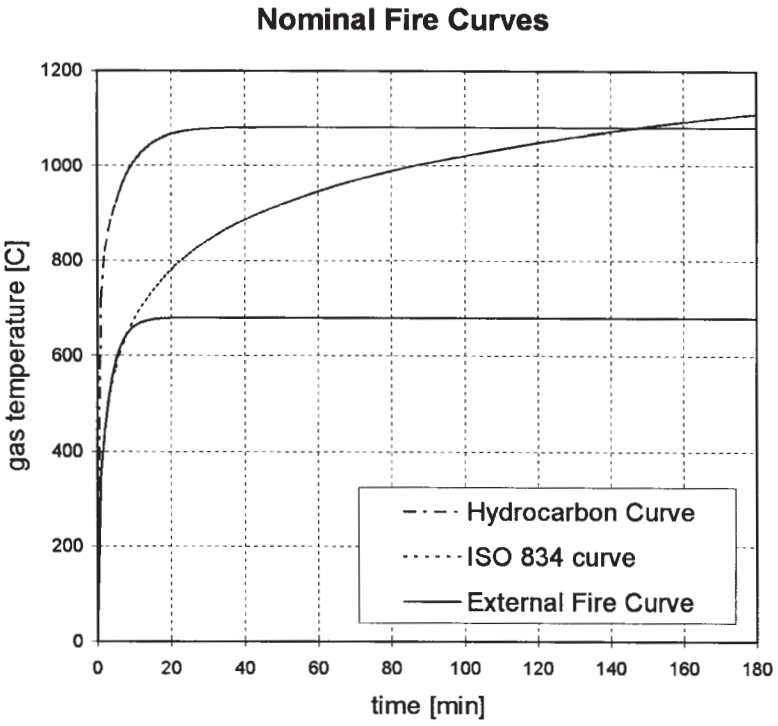

Figure 3-1: Nominal Fire Curves

As an alternative to nominal fire curves, thermal actions for internal members may be based on a parametric equation ("Parametric Fire Exposure"). See Figure 3-2.

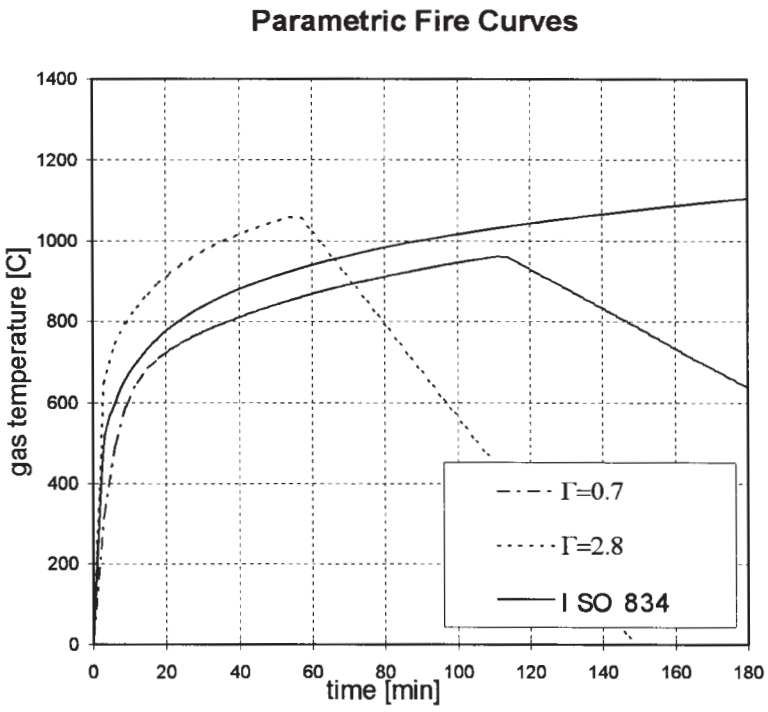

Figure 3-2: Parametric Fire Curves

A higher level of complexity of a model generally means that more - and more detailed- input data is needed [3-1]:

- the total amount of combustion energy per unit of floor area, represented by the fire load density (see chapter 4);
- the so-called opening factor, representative for the rate of heat release and the heat loss through the ventilation flow (see chapter 5 and 6);
- the thermal inertia of the boundary enclosure, representative for the convective heat losses through the solid boundaries (see chapter 7).

4 FIRE LOAD DENSITY

4.1 CONCEPT

The fire load Q in a fire compartment is defined by the total energy liable to be released in case of fire. Part of the total energy will be used to heat the compartment (walls and air), the rest of the energy will be released through openings.
Building components such as wall and ceiling linings, and building contents, such as furniture, constitute the fire load. Divided by the floor area, the fire load Q gives the fire load density q_f.
In EC 1, the characteristic fire load density is defined by the following equation:

$$q_f = \frac{1}{A_f} \sum_i \left(\psi_i \cdot m_i \cdot H_{ui} \cdot M_i \right) \qquad (4\text{-}1)$$

where:

M_i = the mass of the material i (kg)
H_{ui} = the net calorific value of the material i (MJ/kg) (see Table 4.2)
m_i = the factor describing the combustion behaviour of the material i
Ψ_i = the factor of assessing protected fire load of the material i
A_f = the floor area of the fire compartment

$H_{ui}.M_i$ represents the total amount of energy contained in material i and released assuming a complete combustion.
The 'm' factor is a non-dimensional factor between 0 and 1, representing the combustion efficiency: m = 1 corresponds to complete combustion and m = 0 to the extreme situation in which a combustible material contributes no heat at all to the fire. The m-factor is a function of the type of fuel (solids, liquids) and its geometrical properties (porosity, massivity) and the fire conditions (temperature, radiation, oxygen content, etc.). In the next paragraph, the m-factor is described.

The Ψ-factor is introduced to take into account protection of the fire load, for example by putting it inside a cabinet. It has a value between 0 (complete protection for the full fire duration) and 1 (the protection has no influence on the energy release). The protection may reduce the energy release, but often does so for a limited period of time, which depends on the fire conditions (radiation, temperature). This is not reflected in the present concept of the Ψ-factor, since this factor is assumed to be time independent. The protection factor is described in the paragraph below.

According to EC 1, the fire load density may be determined on the basis of a national fire load classification system or -for an individual project - by performing a fire load survey.

The classification on the basis of the occupancy of the fire compartment calls for a statistical approach. An overview of statistics available in Europe is well represented in a CIB/W14 workshop report [4-1]. In Table 4-3 a summary is given of the data, as an operational guidance on application.

The calorific value of a material can be measured by using the "Calorific Bomb" test method. In this test -at high temperature, pressure and O_2 percentage in a closed environment- the material is burnt, and the total energy released is measured. Under these conditions, all combustible materials will burn completely, thus giving the "calorific" value. The same can be done for composite materials. For a number of typical materials the calorific value is given in Table 4-2. The concept of fire load density can be used for post-flashover fires; the conditions in the fire room depend heavily on the fire load density in the room. In the pre-flashover stage the effect of the fire load density is not so dominant; other parameters play a more important role.

From experiments with natural fires the conclusion can be drawn that for post-flashover fires the fire load density q_f calculated as the fire load per unit floor area [MJ/m^2] is important, rather than the fire load itself. Sometimes another definition of fire load density is proposed as the fire load per unit area of enclosure (walls + ceiling + floor). It is true that the total heat lost to the surfaces depends on the total surface of the boundaries, but this effect is considered in the fire modelling. This effect should not be mixed with the determination of the fire load density. The use of fire load density q_f calculated as the fire load per unit floor area [MJ/m^2] is therefore recommended.

4.2 DISTRIBUTION OF FIRE LOAD (DENSITY) IN A BUILDING

Buildings are normally divided in so called fire-compartments. The individual fire compartments are separated with fire resisting elements. The basic idea is that a fire will be contained in the compartment where the fire starts.

The mean fire load density of a complete building is a global parameter, and is felt to be incorrect. In this approach, a high fire load density in one compartment will be compensated if the fire load density in another compartments is low. The maximum fire load density determines the maximum severity of a fire but will not be recognised if the overall mean fire load density in the building is used.

For this project an approach is suggested based on the division of the building in fire-compartments: the fire safety measures for individual fire compartments must be based on the fire load density in that fire compartment.

Note: Hot spots within a fire compartment are not considered explicitly; this approach is based on the assumption that the complete fire compartment is involved in fire. If the difference in fire load density within a fire compartment is large, the best solution is to create a separate fire compartment around such a hot spot.

4.3 COMBUSTION EFFICIENCY: m-FACTOR

4.3.1 INTRODUCTION

As described above, the m-factor is a non-dimensional factor between 0 and 1, representing the combustion efficiency. The m-factor is a function of the type of fuel (solids, liquids) and its geometrical properties (porosity, weight) and the fire characteristics (temperature, oxygen content, etc.).

The determination of the m-factor is not a straightforward procedure. In DIN 18230 [4-6] a systematic approach is used for the determination of the m-factor for different materials and storage types. A table is given with m-factors for a large number of stored combustible goods (variation in type, amount, distribution and density). The data in this table is based on results of a small-scale fire-test, which is – in a summary way – described hereafter.

The fire load is burnt in a small room (2x2x2m) with a standard forced inflow of fresh air. The maximum temperature of a steel plate (= reference element), located just beneath the ceiling, is determined. From a set of reference tests, using well defined wood cribs as fire load, that result is selected, which leads to the same time to reach the maximum temperature in the steel plate, as in the actual test. The m-factor is defined as the ratio of the maximum steel temperature increase in the actual test and in the selected reference test.
The test is not too well suited to determine the m-factor since:

- The measurement of the m-factor is based on the temperature in the room. As a reference element a steel plate is used, simulating the warming-up of an unprotected steel structure in a real building. The temperature ratio is not related to the actual m-factor. In some cases m-factors > 1 are found.
- The amount of ventilation plays an important factor in the test. This effect should be tackled in the fire models, not in the m-factor. In some cases, low m-factors in the test could be due to an excess of fuel in relation to the amount of forced ventilation in the test, leading to outside flaming.

4.3.2 NEW TEST FOR MEASURING THE M-FACTOR

In recent years the O_2 measuring technique has been developed, enabling the accurate measurement of the heat released in a fire by measuring the drop of O_2 percentage in the exhaust fumes. Internationally, experience has been gathered with this technique, for example with the cone calorimeter and the furniture calorimeter. The proposal for a new European reaction-to-fire test (Single Burning Item) uses this technique.

With oxygen depletion a better test method to determine the m-factor can be developed. For the NFSC project this approach has been investigated. With a small-scale test set-up (fire room with dimensions ~ 0,5x0,5x0,5 m) some tests have been performed to evaluate the possibilities in practice. In a background document [4-4] the test set up is described in detail, and test results are given. In this paragraph the basic idea of the method is explained.

The test set-up consists of a small room with an opening in one wall. To obtain post-flash-over conditions ($T_{gas} > 600°C$) the room is fitted with a propane gas burner. The room is placed under an extraction hood, so that the O_2 concentration in the exhaust gases can be measured.
The basic idea of the m-factor is that a product will only partly contribute to the heat release of the fire. The rest of the material will remain unburned or will leave the compartment as unburned gases. The goal is to measure the m-factor of a combustible under post flashover conditions, since the fire load density is only relevant under these conditions.

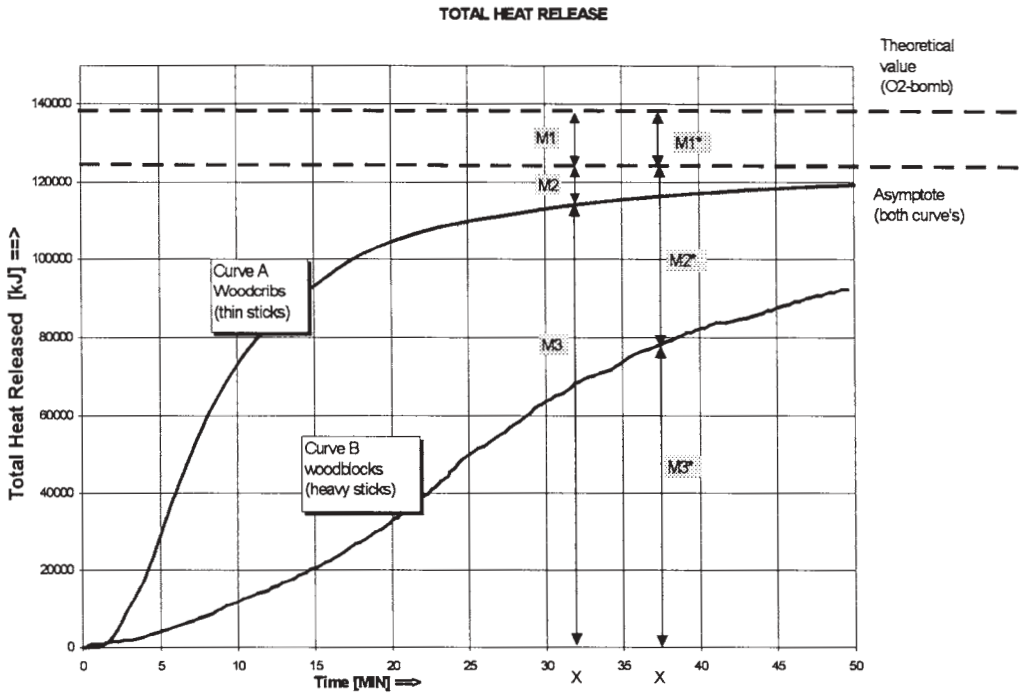

Figure 4-1: Total heat released by two types of wood cribs.

In Figure 4-1 a sketch is given of the total heat released for two tests. In both tests, wood cribs are used as test material. Curve A is a test on a wood crib with very thin sticks, while curve B is a test on a wood crib with much heavier sticks. The amount of wood (kg) used in both tests is the same (4 kg wood).
In this example, the wood crib with thin sticks burns faster than the crib with heavy sticks. The trend of the curves allows the conclusion that the total heat released after a very long time is roughly the same for both cribs. This is not surprising since the amount of wood is the same.
Take the m*-factor equal to (M3)/(M1+M2+M3) (see Figure 4-1). This will lead to a time dependent m-factor of the product. The time X at which the m-factor is calculated should be chosen equal to the relevant fire duration. The basic idea is that there is no need to take the part of the combustible into account that will only burn after a long time, while the expected fire duration is much shorter. For easy use the m-factor of a product could be given in a table for resp. 20, 30, 60 etc minutes relevant fire duration.

Experiments should be carried out on various materials to check the range of m-factors that will be found, and the validity of the proposed approach. Pending the results of systematic tests, a value of m = 0,8 is suggested for practical situations.

4.4 PROTECTION FACTOR

Experiments to establish the effect of distribution and protection of the fire load for different types of buildings have been reported. Experiments have been carried out to analyse the effect of protection of the fire load on the total heat released in a fire in office buildings. For example a certain amount of papers in a closed cupboard could behave differently from the same amount of paper stacked on a desk. The basic idea is that not all the available fire-load will be involved in the fire; a protection factor ψ for the fire load is proposed to account for this effect.

This matter has been evaluated by Bryl [4-7] doing experiments in which not only the fire load in the cupboard but also the fire load next to the cabinet has been varied. The following conclusion can be drawn from this research:
The 'protection' effect of a normal (non fire resistant) cabinet is only significant in the situation that the fire load in the room outside the cabinet is very low, and thus no substantial fire outside the cabinet can be expected. In all other cases, a substantial fire can be expected outside the cabinet. The experiments show that after some time most of the fire load in the cupboard will become fully involved in the fire. The reason is that the cupboard (or parts of it, like doors, shelves etc.) will collapse, exposing the fire load inside.

For the NFSC research we propose:

- Combustible materials that are protected by constructions with a fire rating that is high enough (e.g. fire cabinet, cable insulating with a sufficiently high fire resistance rating) will not become involved in the fire.
- The rest of the fire load in the compartment will become completely involved in the fire.

4.5 ESTIMATING FIRE LOAD DENSITY

The fire load densities in a building have to be established. This can be done in a deterministic way, by summing all fire loads present in the various fire compartments. When asking for a permit for new building this deterministic approach is often not accepted, since the fire load density is a random variable. If information was available on the fire load density in various building types (office, hotel etc), the value for a new building could be deduced on the basis of statistical considerations. In this research, an analysis has been done on the information available on fire load density in literature. In the years between 1970 and 1986, substantial research has been done on the fire load density in buildings. Since then, little new information has become available.

In the Design Guide on Structural Fire Safety [4-1], the available data on the variable fire load density in existing buildings has been collected. This report is the most extensive publication that is available on fire load density in buildings.

Data on the variable fire load density is included for a large number of different types/classes of buildings. This data is assembled by inspection of a large number of different buildings in a number of countries.

The fire load density, and often also the standard deviation is included in the tables. The standard deviation in most tables is quite large. The main reason for this high value of the standard deviation is the large spread in fire density between the different buildings and rooms of one type. Especially in storage buildings a large spread can be expected due to the variability in the amount and type of stored goods in a building. For building types like offices, schools and dwellings, the expected scatter in fire load density is smaller.

The available data in the Design Guide is given in a number of tables for different building types and countries, each in a different format. This is the reason that the data is not easily accessible. In order to improve the ease of use, the data for typical buildings should be summarised - in one table in one format- for easy access by users. Unfortunately, very little information is available as to the number of measurements taken to obtain the tables in the Design Guide. This is why it was not possible to deduce a consistent table using all the information (hundreds of building types) in the design guide.

A more realistic approach is chosen. In the table only the building types are included that are supposed to show a small variation in fire load density due to the character of the building (offices, hotels, station, sports arena etc... See Table 4-3).

Table 4-3 includes the mean value and the fractile values for a number of fractiles (80, 90 and 95%) and the standard deviation. These values are calculated from the mean values using a "Gumbel" distribution. In this calculation a variation coefficient (standard deviation/mean) of 0,3 is assumed.

A similar approach has been adopted in the Australian "Interim Fire Engineering Guidelines" [4-2], which is actually based on the Swiss data [4-9] and the British Draft Code [4-3].

4.6 DESIGN VALUE FIRE LOAD DENSITY

The data on fire load density in Table 4-3 can be used for the calculation of the temperature development in a fire compartment based on natural fires, incorporating geometry, openings, wall materials etc. For example with the gamma fires in EC1 [4-8] the gas temperature in the compartment and the resulting steel temperature is calculated for various fire load densities. Figure 4-2 shows the effect of the (design) fire load density on the maximum steel temperature in a specific building for three values of fire load density.

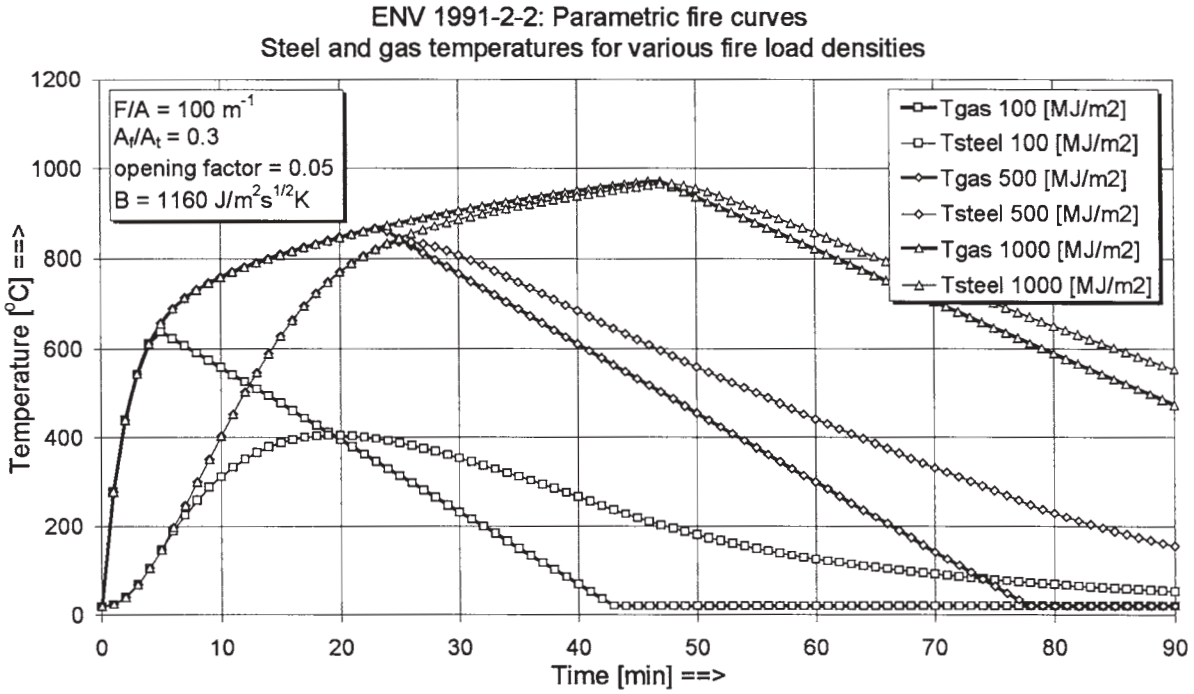

Figure 4-2: Parametric fire curves; Steel and gas temperatures for three fire load densities.

This figure is based on a bare steel beam (3-sided heating, statically undetermined) in an office building. For the design of a bare steel beam (Section Value = 100 m^{-1}) three values for the fire load density are used.

The choice of the design value for the fire load density (what fractile is to be used) has important consequences for the structural fire design. This is illustrated in Table 4-3 for a certain design situation. For various design values of the fire load density, in this table the minimum allowable critical steel temperature (or maximum allowable degree of loading) of a steel beam is given, for which the steel beam can remain unprotected without collapsing under natural fire conditions. Also an indication is given of relative failure probabilities, given a fully developed fire.

Design fire load density fractile [%] / [MJ/m^2]	T (critical; Design) [°C]	Allowed load factor (%)	Probability * of failure given per building life
50% / 285	525	70	0,45
80% / 354	642	35	0,17
90% / 410	709	20	0,05
95% / 464	765	16	0,016

Table 4-1: Critical steel temperature and probability of failure for several design fire load density (fractiles)

Key to the fire design is that mechanical load on the beam is chosen such, that the critical steel temperature just equals the maximum steel temperature for a given value of the fire load density.

The following main assumptions hold for the calculations:

- fire load density: mean:285; standard deviation: 96 MJ/m^2;
- temperature development according to a so-called 'gamma-fire' with opening factor: 0,15 (m$^{-1/2}$); thermal inertia: 1160 (J/m^2.s$^{1/2}$.K);
- steel beam: three sided exposed (section value: 100 m^{-1});
- steel grade: S235 (yield stress at room temperature: 235 N/m^2).

Only the fire load density and the yield stress of the steel are taken as stochastic parameters. With respect to the fire load density, a distribution is assumed as suggested in Table 4-1. The design yield stress of steel at room temperature is taken as the 5% fractile (= characteristic value).
From this table it can be concluded that, for an increasing value of the design fire load density:

- the maximum allowable degree of loading decreases significantly, i.e. the beam must be increasingly over dimensioned;
- the failure probability decreases significantly, i.e. a more safe design is achieved.

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* Note that in this context, the relative failure probabilities are calculated under the assumption that flashover has occurred. Hence, in order to arrive at absolute failure probabilities, other aspects should be incorporated e.g.:
- the probability occurrence of a fire (typical value: 10^{-5} / (year.m^2)
- the probability of occurrence of flash-over, given a fire (typical value: 1/10).

4.7 CONCLUSION

All buildings are divided in fire compartments. The fire load density should be assessed for all individual fire compartments. The fire load density can be determined in two ways:

- From Table 4-3, according to the occupancy of the fire compartment.
- From a survey of the actual amount of combustibles in the compartment. With equation (4-1) and Table 4-2 the fire load density can be calculated.

For the design of elements, a design fire load density for the specific building type can be found in Table 4-3. The fractile still has to be chosen. For a specific element, a higher fractile for the fire load density will lead to higher 'design critical steel temperatures' and lower allowed load factors. This results in a lower probability of failure of the element. This probability approach is handled in the scope of WG4 and WG5 of this research project.

Solids	[MJ/kg]	Liquids	[MJ/kg]
Anthracite	34	Gasoline	44
Asphalt	41	Diesel oil	41
Bitumen	42	Linseed oil	39
Cellulose	17	Methanol	20
Charcoal	35	Paraffin oil	41
Clothes	19	Spirits	29
Coal, coke	31	Tar	38
Cork	29	Benzene	40
Cotton	18	Benzyl alcohol	33
Grain	17	Ethyl alcohol	27
Grease	41	Isopropyl alcohol	31
Kitchen refuse	18		
Leather	19		
Linoleum	20		
Paper, cardboard	17		
Paraffin wax	47		
Foam rubber	37		
Rubber isoprene	45		
Rubber tire	32		
Silk	19		
Straw	16		
Wood	19		
Wool	23		
Particle board	18		

Plastics	[MJ/kg]	Gases	[MJ/kg]
ABS	36	Acetylene	48
Acrylic	28	Butane	46
Celluloid	19	Carbon monoxide	10
Epoxy	34	Hydrogen	120
Melamine resin	18	Propane	46
Phenol formaldehyde	29	Methane	50
Polyester	31	Ethanol	27
Polyester, fibre reinforced	21		
Polyethylene	44		
Polystyrene	40		
Petroleum	41		
Polyisocyanurate foam	24		
Polycarbonate	29		
Polypropylene	43		
Polyurethane	23		
Polyurethane foam	26		
Polyvenylchloride	17		
Ureaformaldehyde	15		
Ureaformaldehyde foam	14		

Table 4-2: Net calorific values of typical materials

	Stand. Deviation	Mean	80% fractile	90 % fractile	95 % fractile	Gumbell Alpha
Dwelling	234	780	948	1.085	1.217	0,0054782
Hospital	69	230	280	320	359	0,018578
Hotel (room)	93	310	377	431	484	0,013784
Library	450	1.500	1.824	2.087	2.340	0,002849
Office (standard)	126	420	511	584	655	0,010174
School	85,5	285	347	397	445	0,014993
Shopping centre	180	600	730	835	936	0,007122
Storage buildings	*	*	*	*	*	*
Theatre (cinema)	90	300	365	417	468	0,014243
Transport (public space)	30	100	122	139	156	0,04273

* *Depends too much on the actual stored goods (storage type, storage height, density etc.). No design values can be given.*

Table 4-3:Data on fire load density for different buildings and functions (variable load only Gumbell distribution assumed, see WG1 of this research).

5 RATE OF HEAT RELEASE (RHR)

5.1 CONCEPT

The fire load defines the available energy but the gas temperature in a fire depends more in particular on the rate at which this energy is released. A same fire load burning very quickly or smouldering can lead to completely different gas temperature development.

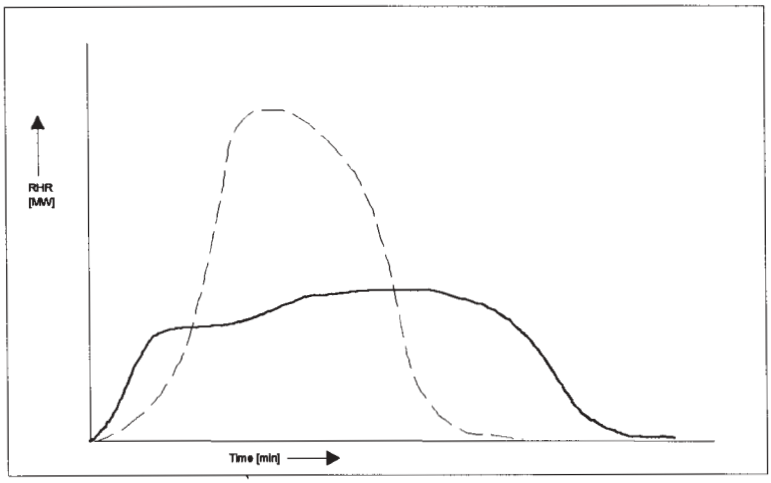


Figure 5-1: Two RHR curves corresponding to the same amount of fire load, as the surface beneath both curves is the same.

The RHR is the source of the gas temperature rise, and the driving force behind the spreading of gas and smoke. A typical fire starts small and goes through a growth phase. Two things can then happen depending whether during the growth process there is always enough oxygen to sustain combustion. Either, when the fire size reaches a maximum, the RHR is limited by the available fire load (fuel controlled fire). Or if the size of openings in the compartment enclosure is too small to allow enough air to enter the compartment, the RHR is limited by the available oxygen and the fire is said to be ventilation controlled. Both ventilation and fuel-controlled fires can go through flashover. This important phenomenon marks the transition from a localised fire to a fire involving all the exposed combustible surfaces in the compartment. The two regimes are illustrated in Figure 5-2, which presents graphs of the rate of burning vs. the ventilation parameter $A_w \sqrt{h}$, with A_w being the opening area and h being the opening height. Graphs are shown for different fire load densities. Starting on the left side of the figure in the ventilation controlled regime, with increasing ventilation parameter the rate of burning grows up to the limiting value determined by the fire load density and then remains approximately constant (fuel controlled region).
In the Annex B of [5-1], where no value of RHR appears, a basic assumption has had to be made on the rate of burning. In this Annex, the fire is supposed ventilation controlled and the RHR is assumed to be proportional to $A_w \sqrt{h}$.

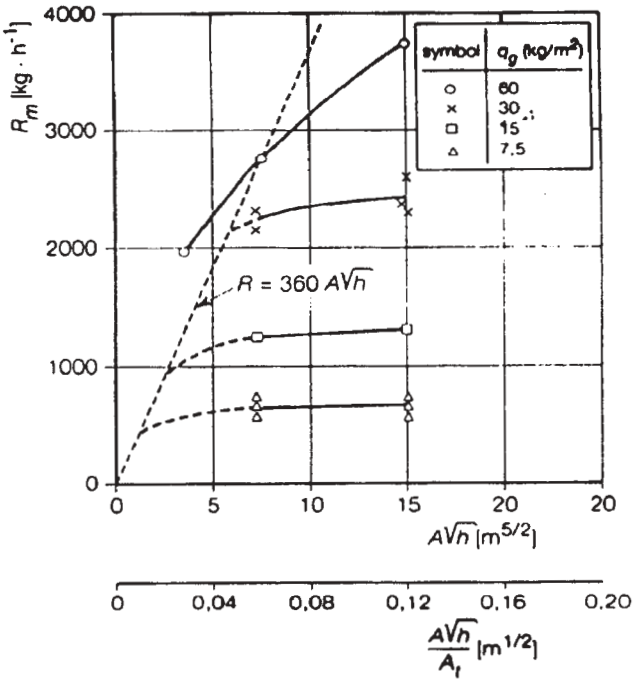


Figure 5-2: Mass rate for different fire load densities.

There are various documents in which either example of RHR curves or calculation rules the RHR are given.

a) Formula to calculate the RHR in case of fully engulfed compartment.

It is possible to calculate the RHR from the variables such as the compartment and vent dimensions along with the fire load. In Eurocode [5-1] these equations are one for fuel-controlled fires and another for ventilation controlled fires, where the lower of the two is taken as the value for the RHR.

b) RHR given by per unit area in case of localised fire.

Values of the RHR per m^2 (RHR_f) are given in other documents [5-2], [5-3] and [5-8]. The values of RHR_f and of the fire area (A_{fi}) enable to calculate the maximum value of the RHR.

c) Experimental data.

It is also possible to find results of tests of which the RHR graphs are given. These include "Initial Fires"-Lund 1993 [5-4], which contains a large number of daily, house hold and generally encountered combustibles. There is also the Fire Assessment Method "Hazard" [5-8] which contains a database from where one can extract the RHR. The two sources sometimes overlap. The Hazard file contains around 100 examples and the "Initial Fires" around 170. Another source for finding this type of information is, like Hazard, a fire simulation programme called "Argos" [5-7].

5.2 USE OF FORMULA TO CALCULATE THE RHR IN CASE OF FULLY ENGULFED COMPARTMENT

5.2.1 KAWAGOE FORMULA

In the case of ventilation controlled fires Kawagoe proposed in 1958 an empirical equation relating the mean rate of combustion to the dimensions of openings [5-11].

$$R_m = 0{,}091 * A\sqrt{h_a} \qquad (5\text{-}1)$$

where:

R_m = mass loss rate (kg/s)
A = total opening area of the fire compartment (m^2)
h_a = mean height of the fire compartment openings (m)

Afterwards other authors proposed different values among 0,083 to 0,12 instead of the constant 0,091 [5-12], [5-13], [5-14] and [5-15].
From the mass loss, the RHR can easily be deduced by multiplying it with the calorific value of the combustible (J/kg).

5.2.2 EUROCODE (ENV 1991-2-2, ANNEX C) [5-1]

Eurocode 1 is one of the sources in which a calculation method for determining the RHR can be found. In Annex C the equation below is specified:

$$R = \min\left[L/\tau_F\ ,\ 0{,}18\cdot(1-e^{-0{,}036\eta})\cdot A_w\cdot\sqrt{h_a\cdot W/D}\right] \qquad (5\text{-}2)$$

where:

R =	rate of burning	(kg of wood/s)
L =	fire load ($=A_f{*}q_f$)	(kg of wood)
τ_F =	free burning fire duration (assumed to be 1200)	(s)
A_w =	sum of window area on all walls ($A_w = EA_{wi}$)	(m^2)
h_a =	weighted average of window heights on all walls ($h_a = A_{wi}.h_i/A_w$)	(m)
W =	width of wall containing window(s)	(m)
D =	depth of fire compartment	
η =	$A_T/(A_w.h^{1/2})$	($m^{-1/2}$)
A_T =	all surfaces minus windows	(m^2)

These two terms, of which the minimum must be taken, indicate whether the fire is ventilation or fuel bed controlled. The first term in the equation: L / τ_F is the term which determines the RHR under fuel bed controlled conditions and the second term: $0{,}18.(1\text{-}e^{-0{,}036\eta})\ A_w\ (h_a\ W/D)^{1/2}$ is the term which determines the RHR under ventilation controlled conditions.

It will clear that the fuel-controlled equation is not very accurate because it assumes all the fuel-controlled fires to have duration of twenty minutes.

With the Eurocode 1, this value corresponding to the maximum RHR is the only value which one is able to extract, no indication is given concerning the time it takes to reach, and drop down from the level of maximum RHR and concerning the shape of the RHR-curve as a function of the time during the rise and decay phase.

According to test results it is generally assumed that the rate of burning is more or less constant and corresponds to the maximum RHR during the period of fully developed fire. During this period the weight of the fire load drops from 80% to 30% of its original value (Figure 5.3).

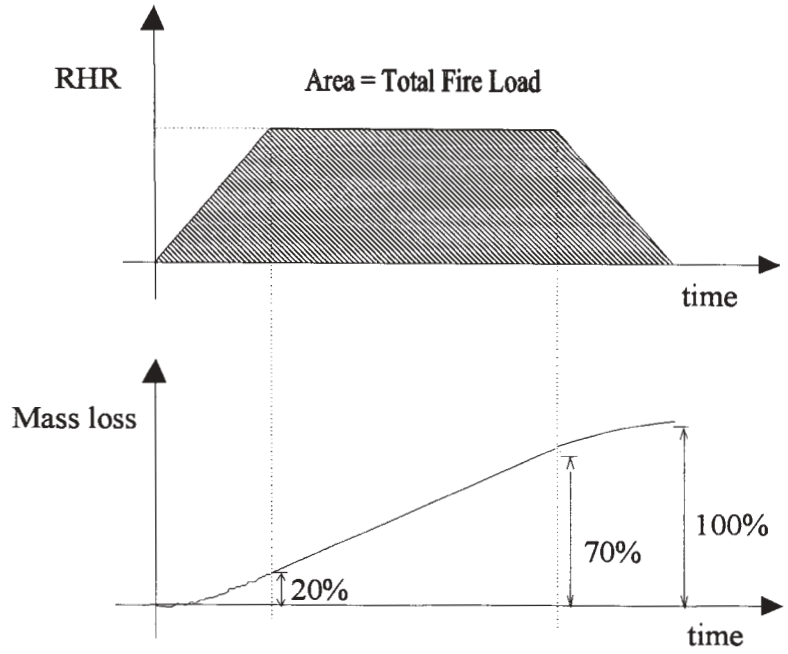


Figure 5-3: RHR and Mass loss as a function of time during a fire test.

5.2.3 BSI 96/540493 (DRAFT FOR PUBLIC COMMENT) [5-2]

The Bsi 96/540493 [5-2] appears to be, in general (concerning the RHR), of the same format as the above mentioned Eurocode. It does however offer a greater source of additional information. The Bsi also contains a guideline which covers the initial and terminal stages of the fire, which no other calculationary procedures do.
Although the format is similar to the Eurocode, the Bsi has a slightly differing equation base. This is illustrated below:

Fuel bed controlled fires: $R_f = L / \tau_F$ (same as EC)

where:

R_f = burning rate
L = fire load (kg of wood)
τ_F = effective fire duration (1200) (s)

Ventilation controlled fires: $\mathbf{R_f = 0{,}02 \cdot \sqrt{\left(A_T \cdot (W_c / D_c) \cdot A_w \cdot \sqrt{h_a}\right)}}$

where:

A_w	= area of ventilation openings	(m^2)
A_t	= area of enclosing surfaces of the compartment	(m^2)
A_T	= A_t-A_w	(m^2)
W_c	= width of wall containing openings	(m)
D_c	= depth of the compartment	(m)
h_a	= height of ventilation openings	(m)

The way in which the various equations yield different results to the Eurocode 1 (EC1) can be seen in Figure 5-4 [5-6, 5-16]. These graphs show that although there is a slight difference between the two, the difference can be neglected.
Figure 5-4 shows also that the equations of [5-1] and [5-2] give results rather close to the RHR measured during tests.

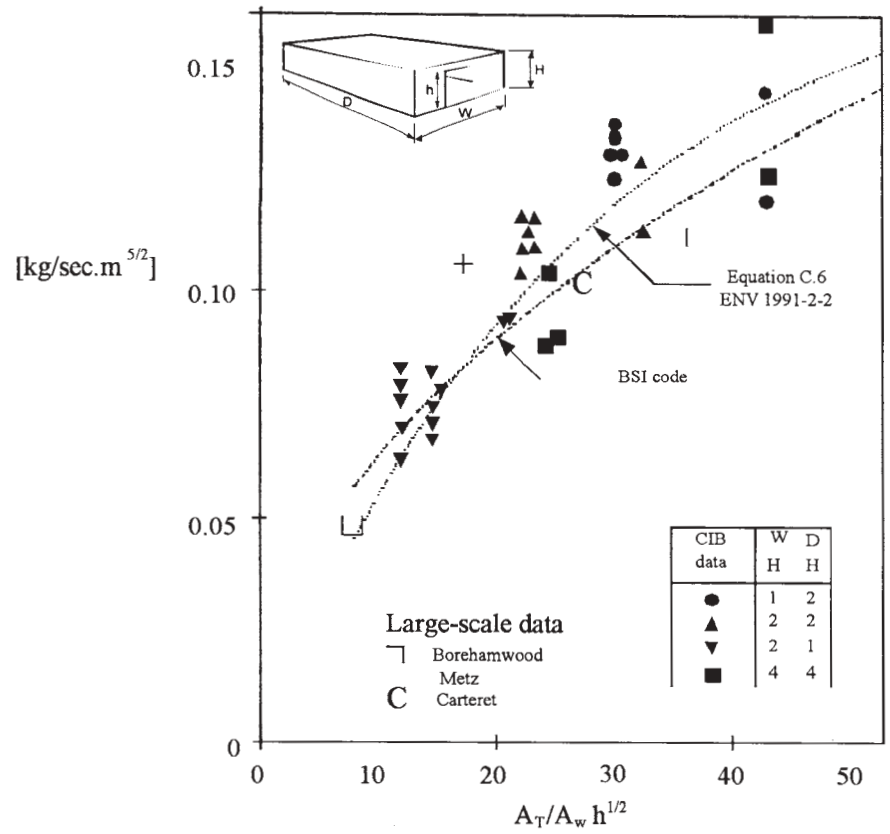


Figure 5-4: Variation of the rate of the burning rate R [kg wood / s] with compartment size data and ventilation data (h, A_w)

5.2.4 RISE AND FALL PHASES OF A RHR-CURVE

The codes mentioned before cover only the maximum value of the rate of heat release. There is however information in the British standard [5-2] which deals with the rise to this maximum value (see Figure 5-5).

$$RHR = (t / t_\alpha)^2$$

where:

RHR	=	Rate of heat release of the fire during growth phase	(MW)
t	=	time	(s)
t_α	=	time constant given in Table 5-1	(s)

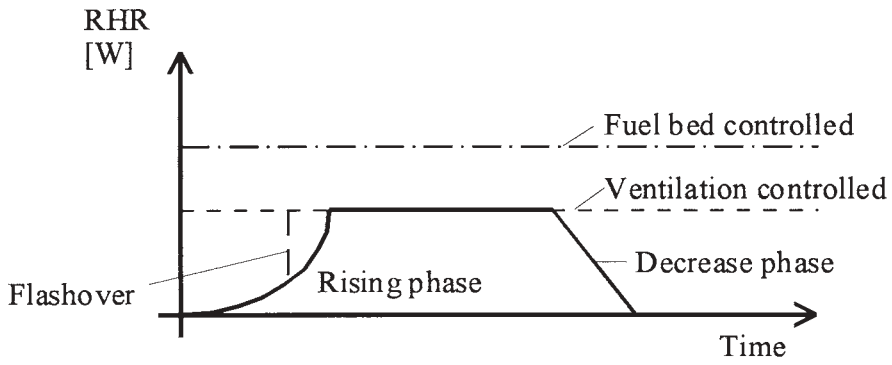


Figure 5-5: Rate of Heat Release vs. Time: Three phases are recognised: rise, stationary (post flashover) and decrease.

The fire growth parameter varies according to fire and some guidance towards the classification and determination of this parameter is given in the codes and is shown hereafter.

Occupancy	Fire growth rate	Time constant $T_{\alpha(s)}$
Storage building (little combustible materials)	Slow	600
Dwelling	Medium	300
Hotel reception	Medium	300
Hotel bedroom	Medium	300
Office	Medium	300
Storage building (cotton, polyester sprung mattress)	Medium	300
Picture gallery	Fast	150
Shop	Fast	150
Storage buildings (full mail bags, plastic foam, stacked timber)	Fast	150
Chemical Plant	Ultra fast	75
Storage buildings (alcohol pool fire, upholstered furniture)	Ultra fast	75

Table 5-1: Fire Growth Rate t_α depending on the building occupancy

With the first stage of fire growth determined, the maximum value of RHR from the equations for fuel bed or ventilation controlled fires can be used to chart the path of the fire until the stage at which it starts to decay.

There is no information about the decay phase in [5-1]. In [5-2] and [5-17] this decay phase is assumed to show a linear decrease of the RHR. Formulae are given to calculate the time of commencement of the decay period and the duration of the decay period. Based on test results, the decay phase can be estimated to start when approximately 70% of the total fire load have burnt.

5.3 RHR PER UNIT OF AREA IN CASE OF LOCALISED FIRE

In some special cases it is obvious that the fire will remain localised due to the distribution of the fire load and the dimensions of the compartment (see [5-19]). For instance in an exhibition hall, the fire size corresponds to the dimensions of a stand. In addition to the area on fire, the RHR per unit area (RHR_f) has to be provided.

If the RHR_f and the Fire area can be established then using the following equation the RHR can be derived:

$$RHR = RHR_f \cdot A_{fi}$$

where:

RHR	=	Rate of Heat Release [MW]
RHR_f	=	RHR per unit of floor area [MW/m^2]
A_{fi}	=	Area of the fire

The RHR_f is equal to 0,25 MW/m^2 for office buildings and to 0,5 MW/m^2 for retail buildings according to [5-2]. Similar values are found in Standard for Smoke and Heat Evacuation [5-3, 5-18]. In the Belgian Standard [5-3], it is advised to use 0,5 MW/m^2 if the combustibles are unknown. In fact 0,25 MW/m^2 is a typical value for wood cribs fire and 0,5 MW/m^2 for plastic fire. Otherwise the Annex B of [5-3] provides the RHR_f for storage buildings with various material types and also various heights of the stock of these materials.

An example of a few of the items are given below:

For stacked wood pallets of height 0,5 m	RHR_f=1,25 MW/m^2
For stacked wood pallets of height 3,0 m	RHR_f = 6 MW/m^2
For plastic bottles in cartons, stacked of 4,6 m	RHR_f = 4,32 MW/m^2
For PS insulation board, rigid foam, stacked 4,3 m	RHR_f = 2,9 MW/m^2

These values are the maximum (RHR_f) corresponding to the steady state situation. These values are valid in case of fuel bed controlled fire and can be considered as a good alternative to the rough approach of Eurocode 1 annex C in case of fuel bed control fire (see 5.2.2). Even in case of uniformly distributed fire load an approach based on a localised fire may be used if the fire fighters can guarantee to be in action, for instance 15 minutes after the beginning of the fire. In that case the equation of the rise phase can be applied and enables to deduce a fire size by assuming a given RHR_f (see Figure 5-6 and Table 5-2).

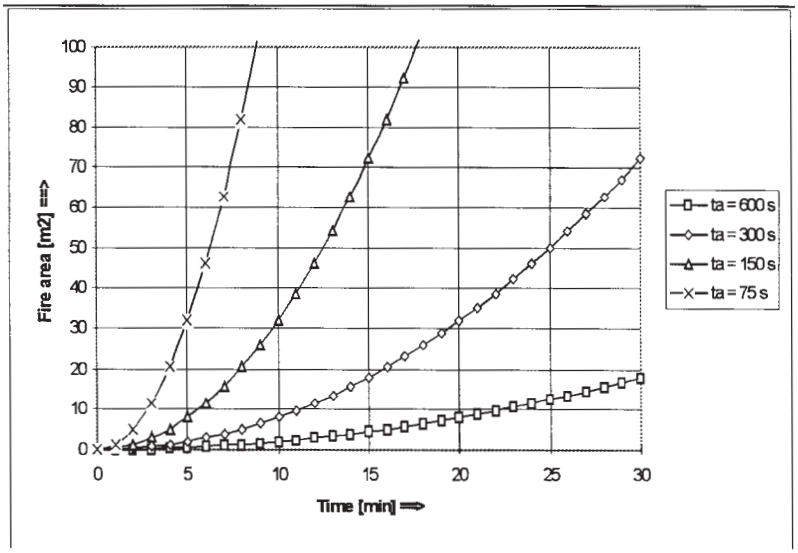


Figure 5-6: Fire area A_{fi} versus time for a RHR_f of 0,5 MW/m^2

Fire growth rate	Fire area, 15 minutes after start of the fire (m^2)
Slow	4,5
Medium	18
Fast	72

Table 5-2: Fire area for a RHR_f of 0,5 MW/m^2 and a firemen intervention 15' after the fire start.

5.4 EXPERIMENTAL DATA

Another way to find an RHR curve is to make a test. Useful techniques for measuring heat release rates in the open were not available until a few years ago, when the principle of oxygen depletion calorimetry was developed. Earlier attempts required the direct measurement of sensible enthalpy, something which is very difficult to do correctly. The oxygen depletion technique, however, has enabled these measurements to be made easily and to good accuracy. The oxygen consumption principle states that within a small uncertainty band, the heat released from the combustion of any common combustible is uniquely related to the mass of oxygen removed from the combustion flow stream [5-15]. This technique has been used and has enabled to establish database of test results.

Different sources of a database nature are available in the literature to extract data for the value of RHR [5-4][5-7][5-8][5-15].

The Hazard [5-8] two-zone simulation model within its framework contains a database where various items are laid out and information on their RHR among other things is given. These items tend to be only items found in the home, for example, chairs, TV's, Christmas trees.... .

This obviously leads to a limitation in the field of use. Although in its particular region of use, it appears to be a very good source of information, since it includes every phase during an RHR curve. Argos [5-7] is another database found within the framework of a fire simulation programme. In Argos, different equations are given for solid material fires, melting material fires, liquid fire and smouldering fires. These equations define the RHR as a function of the fire spread velocity in the horizontal and vertical directions. The numerical values valid for different materials and objects are given in the Argos database.

Another source of test result information is the "Initial Fires" document compiled by the University of Lund [5-4]. This has the same format as the Hazard database but contains more results which are also a little more diverse. In this document one can find information not only on household objects but also objects such as various vehicle types.

CTICM in France has made fire tests (RHR) on new cars (fabricated in 1996) [5-20], on hotel rooms and on real furniture. These experimental data are very interesting, because the majority of fire tests reported in literature have been performed with wood cribs as fuel.

5.5 CONCLUSION

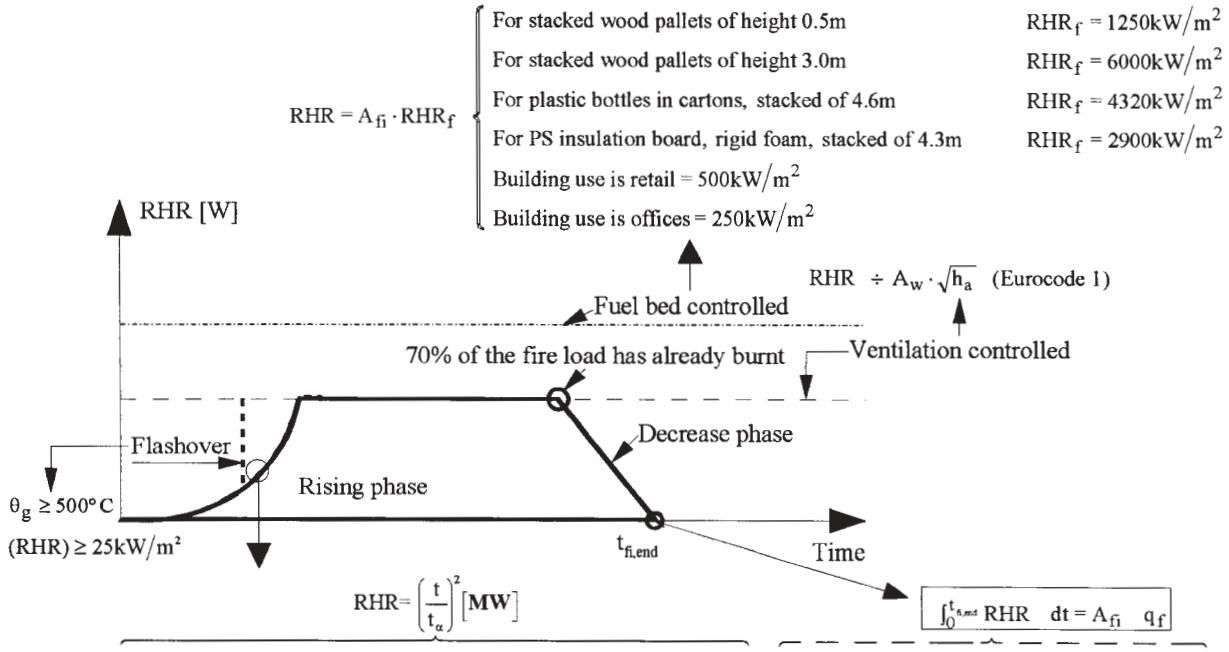
On the whole there is a reasonable range of options open to someone wishing to extract Rate of Heat Release graphs. The actual type of sources vary also and this is an area where the user must use his or her discretion upon choosing the one which will best suit, or offer most realistic results for a given fire scenario. Various points about each of the methods may be worth taking into account when considering the options available. The Eurocode 1 [5-1] is a calculation procedure which takes into account whether the fire is fuel bed or ventilation controlled to calculate a maximum value of the RHR. This method, as shown earlier, agrees quite well to test data, but has the drawback that it doesn't take into account the growth and decline phases for the RHR temperature models. This could be estimated but it seems a far more sensible idea to refer now to the Bsi [5-2] which offers the data required to carry out this phase missing in the Eurocode 1 [5-1].

The Bsi [5-2] enables also to calculate the RHR under ventilation controlled conditions. Although these two codes contain different equations, they yield practically the same results. That's why we propose to adopt the Eurocode formula for ventilation controlled conditions.

On the other hand for the fuel bed control fire, instead of the formula of the Eurocode, it is better to use the values of RHR_f [5-2][5-3][5-18][5-19] and to define the area of the fire, which is the area of the whole compartment in case of fully engulfed compartment.

The final source to be considered is that of test data. This gives the total RHR curve and not only for single elements. There is however the problem that the item one wishes to simulate may not have already been simulated. Also one has to take care if there is not an exact match between what one wishes to simulate and a test object. Because although objects may seem similar they may burn considerably differently. Again one must also bear in mind that test conditions sometimes do not simulate real case fires. Moreover in a real fire several objects are often involved. In general there is enough information given to be able to find the RHR and to simulate a fire with the information which has been covered in this report. Also with the continuation of tests on differing materials the available database will continue to grow and should offer a satisfactory and reliable source to be used in design simulations.

In the following Figure 5-7 the proposal for the RHR curve for the NFSC project is given. The curve includes the growing phase, steady state and the decay phase.
Linear decay phase starts when 70% of the fire load is burnt.



Fire growth rate	Typical equivalent materials	t_α: Time [s] for RHR = 1 MW	Occupancy
Slow	no uniform fire load	600	Picture gallery
Medium	Cotton/polyester sprung mattress	300	Dwelling Hotel reception Office Hotel bedroom
Fast	Full mail bags, plastic foam, stacked timber pallets	150	Shop
Ultra-fast	Methyl alcohol pool fire, faster burning upholstered furniture	75	Chemical Plant

OCCUPANCY	Fire load (80 % fractile) $q_{k,f}$ [MJ/m²]
Dwelling	948
Hospital	280
Hotel (room)	377
Library	1824
Office (standard)	511
School	347
Shopping centre	730
Theatre (cinema)	365
Transport (public space)	122

Figure 5-7: Summary of the proposal for the RHR curve for the NFSC project, including the growing phase, the steady state and the decay phase.

6 FIRE COMPARTMENT LAYOUT

6.1 CONCEPT

When assessing the fire development in compartments, the fire behaviour of boundaries has to be considered. The fire behaviour of boundaries will govern the possible spread of fire to other adjacent compartments. It needs to be evaluated against realistic thermal actions, taking into account the thermal and mechanical properties of the materials used. On the basis of such an evaluation, the size of the fire compartment (floor area, total surface) has to be identified.

Additionally the role played by the openings is important for combustion rate and for the energy exchange with other compartments or the surrounding of the building. On one hand, the area and location of openings through which the flow of fresh air and hot gases will circulate have to be identified. On the other hand, assumptions need to be made on the breaking of glazing and possibly additional openings due to collapsing of doors and walls.

6.2 COMPARTMENT BOUNDARIES

6.2.1 DEFINITION

A building normally consists of number of enclosures (rooms, corridors etc.) An enclosure is a fire compartment if its boundaries (walls, ceiling, floor) keep their integrity during fire and the temperature on the unexposed surfaces is low enough to avoid fire ignition in the adjacent compartments. Alternatively, limits may be set to the radiation from the unexposed side. These criteria are used in the ISO test procedure. However, in the case of natural fires, the behaviour of fire partitions, doors and windows has to be assessed according to the rules given under 6.2.2.

The propagation from one of the small volumes (enclosures) where the fire is very severe to the rest of the compartment necessitates defining locally a confined fire. After a limited period of time (e.g. 15 minutes, depending on the assessed fire resistance of the boundary condition) the whole fire compartment will be considered as fully involved in the fire. The risk of propagation to other storeys has also to be analysed.

In large volumes (such as a storage building), compartmentation is often required by authorities. So the vertical limits of the compartment are rather well defined. However, in the case of a single storey building often there are no requirements with regard to the integrity of the roof. A severe approach is to assume no loss of integrity, since this assumption implies no loss of energy by convection.

6.2.2 ASSESSMENT OF THE FIRE BEHAVIOUR OF SEPARATING ELEMENTS

6.2.2.1 Introduction

For the time being, fire partitions are classified according to a fire resistance test using the ISO-fire temperature-time curve. Integrity and insulation criteria define the fire resistance time of a partition; for example a partition: EI60, a fire door: EI30 or a glazing element: E30.

The purpose of creating fire compartmentation is to delay or to stop fire propagation from one compartment to another.

The assessment of the separating elements can be made by one of the three following methods:

- ad hoc tests;
- expert judgements based on calculations and existing test results;
- direct use of ISO-fire requirements.

These three methods are described hereafter.

For the two first methods, the criteria for assessing the risk of fire spread beyond a given separating element can be expressed as follows:

- loss of integrity due to cracks, melting, gaps,... leading to the passage of hot gases;
- excessive temperature on the unexposed face, leading to ignition of combustible materials at the contact of this face;
- excessive radiation from the unexposed side, leading to ignition of combustible materials which are not in direct contact with the unexposed side of the separating element.

6.2.2.2 Ad hoc tests

This method may be applied to any thermal action (represented by a temperature-time relationship) and to any insulated element (partition wall, door, ceiling, floor, as well as duct, damper...) for which the assessment is required.

The thermal action (design fire) is given by the output of the fire development calculation by considering the worst-case fire scenario. This scenario is the one resulting in the maximum gas temperature and/or the longest duration. If it is not possible to define a worst-case fire scenario, different possible severe scenarios have to be considered.

A fire resistance test is then performed, following the testing methodology developed by CEN or ISO, for the relevant building element, by putting the following changes:

- the temperature-time curve to be followed by the temperature sensors of the furnace is the "natural" temperature-time curve corresponding of the worst-case fire scenario;
- common ultimate states (integrity, thermal insulation and radiation) are considered but the limiting values may differ from those used in a standard fire test, since the actual use and consequently actual risk within the building should be taken into account in a fire engineering approach;
- to continue to record the data during the cooling phase, since due to thermal inertia, the maximum temperatures in the tested element may occur long after the peak of gas temperature.

For the limiting radiation level a critical value of 15 kW/m^2 is proposed for normal buildings and occupancies. This value is based on experimental results as reported for example by Lee [6-8]. The basic idea is that below the critical radiation level a product will not ignite spontaneously, even if exposed to this level of radiation for an infinite period of time.

Only for special occupancies/buildings were highly flammable plastics are used, a lower critical radiation level should be used. Limiting values for several types of plastics can be deduced from Figure 6-1.

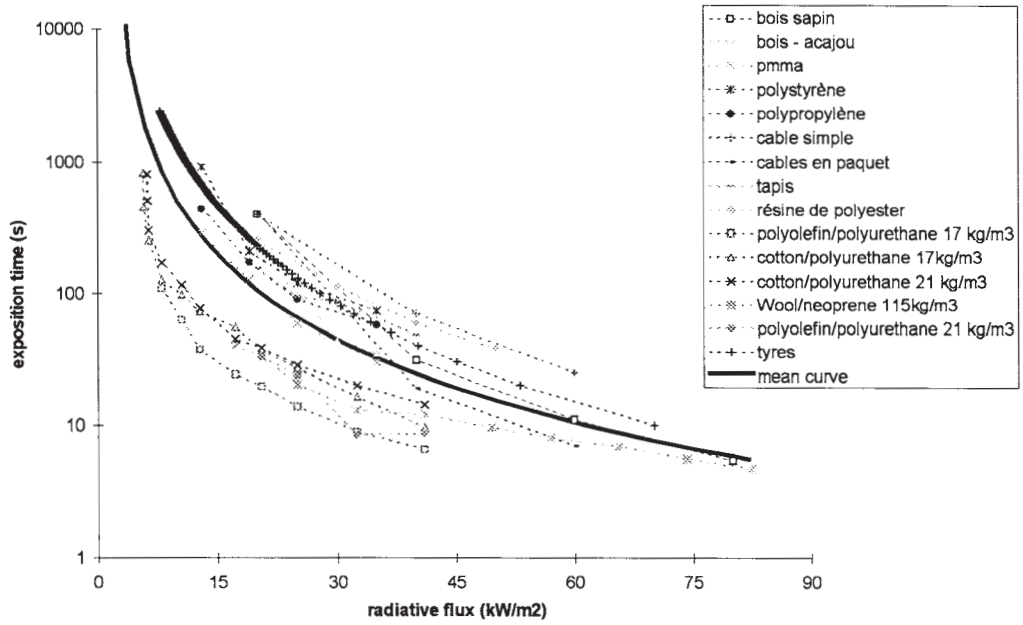


Figure 6-1: Critical radiation heat fluxes according to the exposition time.

Obviously, the approach with ad-hoc tests will be expensive since each specific situation requires a separate test. It can be used for compartments with a specific risk and when the layout of the compartment is representative for many occupancies in a lot of cases (hotel room, cinema...)

6.2.2.3 Expert judgement

Since the current majority of existing data is based on ISO-fire testing, it is necessary to give a methodology to make an optimal use of this information. This can be done by expert judgement, which has to be based on calculation results and assessment of the behaviour of materials at elevated temperatures [6-7].

Calculations have to be made mainly for the temperature field of separating elements and, in some cases, for the mechanical behaviour. However, although it may be assumed that the existing software in these fields is accurate enough, the main problem is to ensure the use of realistic and accurate input data.
In this respect the following steps have to be made when assessing the thermal and/or mechanical behaviour of a given element, which has previously be tested under fire conditions (often the ISO-fire):

- to assess the limit state conditions from the test (critical temperature, critical thermal gradient, critical deformation, critical elongation ...);
- to check the accuracy of the input data (and in the same way the software) by comparing, for the chosen parameter, test results and calculation results using the same temperature-time relationship;
- if the accuracy is sufficient, the same input data and software are used to simulate the behaviour of the same separating element subjected to the design fire (worst-case scenario) or to several possible design fires;
- the result of this (these) calculation(s) will be compared to the failure criteria given above and will be the basis of the expert judgement.

Expert judgement has also to consider the possible occurrence of cracks and melting and the possible change in thermo-mechanical properties in function of the rate of heating, which are generally not taken into account by the existing computer codes.

Since it could be very difficult to have all the necessary data for the expert judgement from a single ISO-fire test result, it should be worth to have, for a given separating element, a set of results obtained with fires of various severity: beside the ISO-fire, there could be a rather fast, an "average" fire and a smouldering fire (Figure 6-2). In this respect the expert judgement could be based on a large range of results:

- fast developing fire, reaching a high temperature of more than 1200°C in, say, 15 minutes, with a relatively short decrease phase;
- the standard temperature-time curve representative of a long and hot fire;
- the smouldering fire for which the temperature is rather low during a long time.

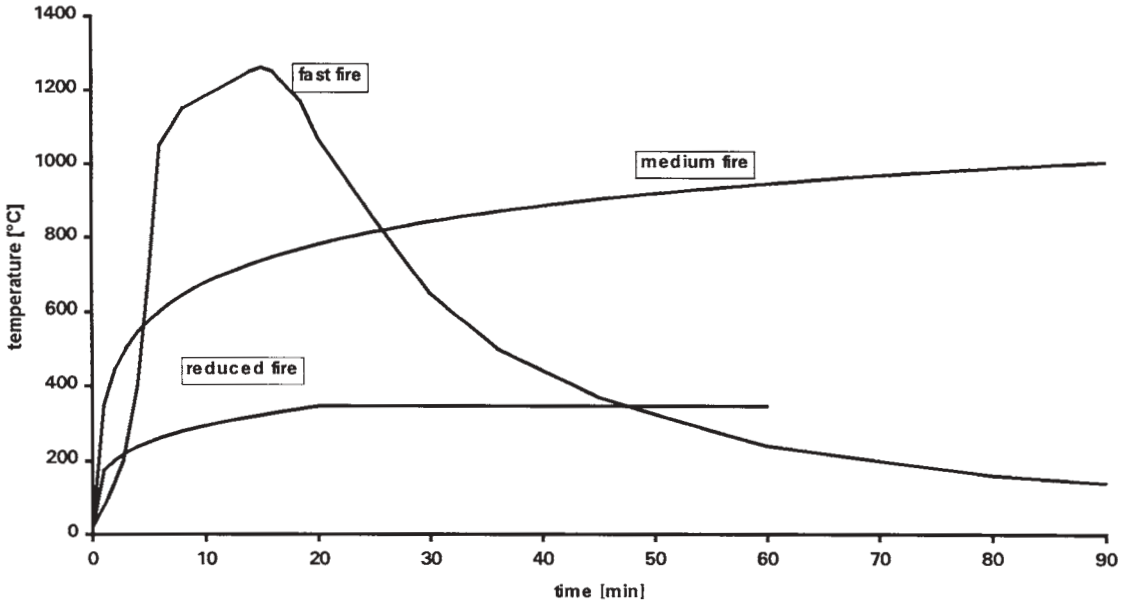


Figure 6-2: Extreme curves.

6.2.2.4 Direct use of ISO-fire requirements

We have to recognise:

- that the behaviour of separating elements under "natural" fires - so far - has not been investigated in depth;
- that the possible methods given above, will generally be very expensive;
- that the existing requirements in industrial countries are generally safe enough to avoid major spreads of fire between compartments.

In this respect a simple way to consider that there will not be any spread of fire from the fire compartment to an adjacent one, if national requirements expressed in terms of ISO-fire ratings, are fulfilled.

This means that if - for a given building, depending on its occupancy - the national rules are requiring a certain fire resistance rating for the separation between compartments, it will be assumed that, whatever the severity of the (natural) fire in a compartment is, the fire will not spread to another compartment if the separating elements fulfil these requirements.

Of course, this is a very rough estimate, which can only be applied for buildings covered by national rules.

6.3 OPENING

6.3.1 DEFINITION

Openings in the form of windows, doors or roof vents are considered. Some of them can have ISO fire ratings. The fire severity depends on the opening size, but the largest opening size does not always correspond to the largest severity of the fire. The severity of the fire depends on the temperature obtained in the compartment but also on the duration of the fire. So the severity of the fire can be defined differently according to the characteristics of the element to be tested (thermal inertia, combustibility).

The following considerations regarding doors, glazing and roof vents are proposed:

- **Doors**
  The doors will be considered always closed if another opening exists (e.g. glazing). If the compartment has no opening, the doors have to be considered opened in order to allow gas exchange with the surroundings, to permit fire development. In case of closed doors, their surface is integrated in the wall surface for heat exchange in the fire development. Moreover, the fire behaviour of the door may also be studied during the fire development in order to analyse its capacity of fire containment.
- **Glazing**
  The behaviour of glazing having an ISO rating has to be assessed with the previous considerations: such glazing will be considered closed during the fire. Heat losses through the glazing by both radiation and conduction should be considered. In case of internal glazing, the radiation criteria, defined earlier, have to be checked. Glazing without an ISO fire rating will be considered opened from the beginning of the fire. Since the main interest of the NFSC project is structural fire safety, this assumption is reasonable: only fires which lead to high gas temperatures in the compartment (say, > 600 °C may endanger the structure. See also Annex D. However, in special cases calculations may be necessary assuming that not all glazing will break. When the size of the opening is larger than 50% of a wall surface, only 50% of that wall surface will define the opening size. This assumption takes into account incomplete breaking of the glass. Very large openings could be otherwise lead to very low temperatures at which the glass is not expected to break (inconsistency!). By way of illustration, the (one zone model) temperature in a compartment ($8x8x3m^3$) with a fire load of 30 kg/m^2 and containing two glazing walls has been calculated. Such a compartment is representative for a meeting room. When considering the complete breaking of the two glazing walls, the maximum gas temperature in the room is 400°C. Considering an opening of 50% of the glazing walls leads to a maximum temperature of 1000°C, which is significantly higher.
- **Roof venting**
  Roof vents will be considered initially opened.

6.3.2 THE OPENING FACTOR

6.3.2.1 Single vertical opening

For the calculation of the expected temperature curve in the compartment, the size of the openings is very important. In previous paragraphs it has been indicated which (part) of the boundary elements should be considered as opening. In simplified models like parametrical fires, the openings are characterised by the so-called "opening factor":

$$A_W \sqrt{H} \tag{6-1}$$

The opening factor determined for vertical openings depends on the opening surface A_w and its height H. This parameter is also used in other models to determine the rate of heat release. See chapter 5. This parameter is easily deducible in case of a single opening in a small room. See Annex B.

The following clauses allow calculating the opening parameter for multiple openings and horizontal openings.

6.3.2.2 Multiple vertical openings

All openings could be considered separately giving a global opening with the following characteristics:

$$A_W = \Sigma A_{Wi} \tag{6-2}$$

$$H = \left[\frac{\Sigma \left(A_{wi} \cdot \sqrt{H_i} \right)}{\Sigma A_{wi}} \right]^2 \tag{6-3}$$

where:

A_{wi} = is the opening area n°i,
H_i = the opening height n°i.

The global parameters (A_w and H) are used to calculate the opening factor.

However, when the openings are not at the same level in the compartment, some of them allow the smoke extraction and others the air entrance, depending on the position of the neutral plane. This is taken into account in more advanced models only.

6.3.2.3 Horizontal openings

Few experimental data are available to give empirical equations for taking into account horizontal openings. Under the assumptions of a homogeneous temperature, a similar theoretical consideration as in Annex B could holds.

Based on the nomogram of Pettersson (see annex B), the following equations can be used to take into account the effect of horizontal openings, by introducing a so-called equivalent opening factor:

$$\left(A\sqrt{H}\right)_{eq} = f_k \left(A\sqrt{H}\right)_{vertical} \qquad (6\text{-}4)$$

where:

$(A\sqrt{H})_{vertical}$ is the opening factor of vertical openings and

f_k a correction factor given by the nomogram given in Figure 6-3.

$$\mathbf{f_k = (1 + 0{,}03(y - 1)) \cdot y}$$

with:

$$y = 2\frac{A_h\sqrt{h_1}}{A\sqrt{h}} + 1$$

The different parameters are given by the Figure 6-3.

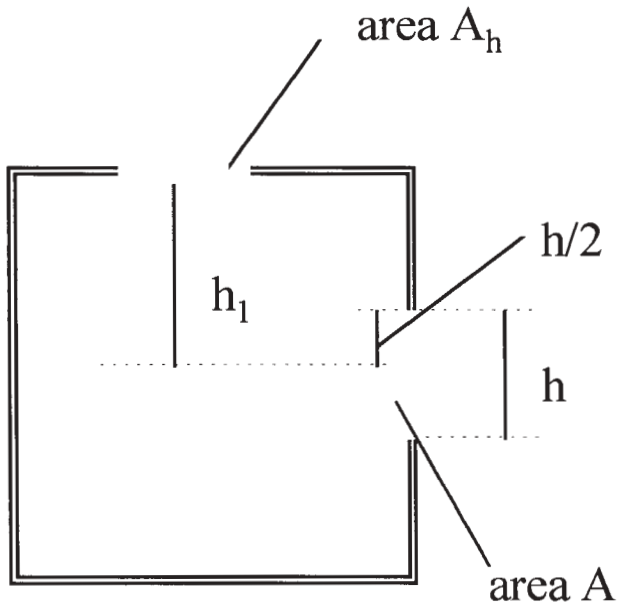


Figure 6-3: Side-view of a compartment with multiple openings: parameters defining the openings.

6.4 MECHANICAL VENTILATION AND PRESSURISATION

Pressurisation and mechanical ventilation are more and more frequently used in fire safety design. To assess their effect on the fire development, calculation models are necessary.

A study of pressurisation in case of fire is difficult. In this research, it will be considered that the objective of pressurisation is always reached. It means that an over-pressurised compartment will be smoke free, if the compartment boundaries keep their integrity.

The mechanical ventilation is often used for smoke and heat exhaust ventilation systems (SHEVS). Their effect on the fire development can be taken into account in calculation codes (e.g. advanced models like CFD). However, the fully engulfed fire conditions may endanger the adequate functioning of the ventilators, since the field of application of ventilators is generally defined for temperatures less than 600°C. The mechanical ventilation has to be considered for localised fires. The ventilators, used as air conditioning but not defined as a SHEVS, will be ignored in fire development studies.

6.5 HEAT LOSS

For the heat released by the burning objects, three parts are distinguished: heating of the gas inside the compartment, loss to the walls, loss to the outside through openings. In order to determine the gas temperature, the heat release and the heat losses have to be assessed. The heat loss through openings is by both radiation and convection.

6.5.1 CONVECTIVE HEAT LOSS

The extraction of hot smoke through windows induces a heat loss. This heat loss is proportional to the mass rate and the temperature of the smoke.
In calculation codes, the heat loss is taken into account in the heat balance. In empirical equations this is done in an implicit way, i.e. by the opening factor.

6.5.2 RADIATIVE HEAT LOSS

When openings are small, the radiative heat loss may be neglected and, when the openings are large - resulting in a low temperature of the smoke - the radiative heat loss through openings may be neglected as well.

In case of fully developed fire, it is recommended to neglect the radiative heat loss through openings when the temperature is low (less than 800°C). When the temperature is high (more than 800°C), neglecting the radiation through openings leads to slightly conservative results. See also Annex B.

6.6 CONCLUSION

Three levels of assessment of the fire behaviour of separating elements are given:

- adhoc tests
- expert judgement
- ISO-requirements

The first two levels give sophisticated methods, but are very expensive. The third level, considering the direct use of ISO-fire ratings, will generally be applied.

Different approaches are given to take into account the ventilation. These approaches are based on a homogeneous temperature in the compartment. The fire is controlled by the ventilation conditions when the openings are small in relation to the dimensions of the compartment. In such cases the opening factor concept (see chapter 5) can be used.

More generally, the opening factor controls of the burning rate also for compartments with vertical and horizontal openings. The opening factor calculated for combined vertical and horizontal openings is used in most cases, as a parameter for a simplified method or to define the rate of combustion controlled by ventilation for advanced models. Extrapolation of this approach to more general cases is not validated.

Pressurisation and mechanical ventilation are more and more frequently used in fire safety design. Their effects are theoretically assessed. Validation is not always simple. No empirical data exist to easily quantify their effects. The problems may be solved case by case, like the effect of the combination of vents and vertical openings in large compartments with Belgian standards [6-3], or smoke evacuation in atria with French regulation [6-4]. Due to limited fire resistance of ventilators, they may not adequately function in fully engulfed fire conditions.

The radiative energy loss through openings may be neglected. This leads to a small over-estimation at low gas temperatures and to a larger over- estimation at high gas temperatures. For example: 50°C over-estimation at a gas temperature of 800°C and 200°C over-estimation at 1.000°C.

7 THERMAL PROPERTIES OF BOUNDARIES

7.1 CONCEPT

The heat loss from the compartment is an important factor for the temperature development in the fire compartment. Heat losses to the compartment boundaries occur by convection and radiation. A substantial amount of heat can also be removed from the compartment by the flow of hot gases through openings.

It has been known for a long time that the heat losses to the compartment boundaries can play a decisive role in determining whether a given fire will develop to flashover or not. This is why even the simpler approaches to fire modelling take this aspect into account.
In this chapter a summary is given on thermal properties. Only the relevant conclusions for the Natural Fire Safety approach are given. In Appendix A, a detailed discussion is given on the subject.

7.2 THERMAL INERTIA: b-FACTOR

The most popular way to take into account the heat loss to boundaries is through the concept of the "thermal inertia" by using the b-factor of the wall material. This b-factor is defined for a homogeneous wall construction by:

$$b = \sqrt{\lambda \cdot \rho \cdot c_p} \qquad (7\text{-}1)$$

where:

λ = heat conductivity in W/mK
ρ = mass density in kg/m^3
c_p = heat capacity in J/kgK

It can be shown that under certain conditions (i.e. "thermally thick" wall, constant surface temperature) the heat flux into the wall depends on the b-factor only.

The thermal properties λ, ρ and c_p are in fact temperature dependent. In annexe A, Table A-1 the data on temperature dependent material properties is summarized. This dependency is relatively weak for building materials, while rather strong for insulating materials. This is the most accurate way to calculate the heat loss. Sophisticated fire models can calculate the loss of heat.

The thermal properties of the boundaries also depend on the moisture content of the materials. In literature there is little known about the effect of the water content on the λ, ρ and c_p–values of the material. In a numerical way, this effect is sometimes modelled by using an approach in which the temperature of each cell is kept at 100 °C, until enough heat has entered the cell to accommodate evaporation of the water.

Another approach is used by assuming a "peak" in the c_p of the material at T=100 °C. Both approaches yield acceptable results for practical use. These calculations however are too complicated in the approach with b-factors.

The parametric fire models in the Eurocode use the b-factor as the single parameter to account for the convective heat losses. For the important case of walls consisting of multiple layers of different materials, an effective value of b-factor is calculated from the contributions of the different layers, according to:

$$b = \sum_i (s_i \cdot c_i \cdot \lambda_i) / \sum_i (s_i \cdot c_i \cdot \lambda_i / b_i^2) \qquad (7\text{-}2)$$

where:
λ_i = heat conductivity of material i, in W/(m·K)
s_i = thickness of material i, in m
c_i = heat capacity of material i in J/(kg·K)
b_i = b-factor of material i, in J/(m^2·√s·K)

The application range of this rule is limited to b-factors in the range 1.000-2.000 J/m^2·√s·K.

The expression has some obvious shortcomings:

- The sequence of the different materials is not accounted for; a brick wall insulated with wood panels gives the same result as a wood panel 'insulated' with a brick wall.
- In extreme but practical cases, the expression leads to unrealistic values for b. Consider a wall consisting of two layers of different materials. If the first layer (heated side) is thermally thick, the other layer will have no influence on the heat flux through the surface (example: well insulated brick). The effective b-factor should be equal to b_1. On the other side, if the first layer is thermally very thin, the effective b should be equal to b_2 (e.g. thin steel sheet covering an insulating layer). The weighing procedure in the expression does not follow these relationships.
- The application range is limited. Most of the practical fire insulation materials fall outside this range; see Table 7.1.

In conclusion:

the use of the EC1 rule for calculating effective b-factors is not recommended. Work has been done to establish an alternative 'rule of thumb' to calculate the effective b-factor. A very safe approach is to use the smallest b-factor of the materials in the sandwich construction as the effective b-factor. In the scope of the NFSC-project activities, WG1 has proposed a partial rule for specific situations.

To illustrate the consequences of the use of the b-factor, in Figure 7-1 the temperature development in a fire compartment (Γ-fires), calculated by means of EC1 for different b-factors, is compared with the results of calculations based on a rigorous treatment of the 1-dimensional heat conduction equation. See also Appendix A. For the boundary construction of the fire compartment - floor area 5 x 5 m^2 - various practical sandwich constructions have been chosen. For this situation the EC-1 rule will lead to unsafe results (underestimate of the temperature)

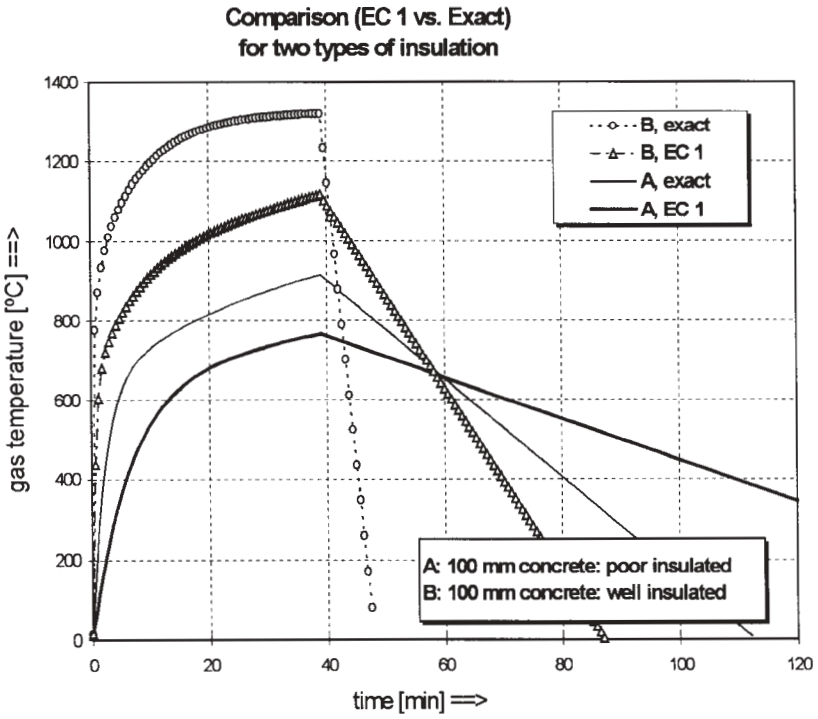


Figure 7-1: Comparison of the b-factor approach with more exact solutions. From this graphs can be deduced that for this specific situation, the EC-1 rule gives unsafe results (estimates too low temperatures)

7.3 CONCLUSION

The heat loss to boundaries (walls, ceiling and floor) of a fire compartment plays an important role in the temperature development in the compartment. The following approach is suggested for the modelling of thermal inertia of the boundaries.
For the modelling of heat losses to the homogenous walls, the use of the b-factor $(\lambda \cdot \rho \cdot c_p)^{1/2}$ is suggested for models that can not calculate the actual loss of heat.
For sandwich constructions, -consisting of a number of materials with different b-factors for the value of the effective b-factor of the construction, the smallest b-factor of the individual materials should be taken, or the rule of WG1 can be taken for some specific situations.

For the NFSC we suggest to neglect the effect of the water content; the thermal inertia (b-factor) for the wall should be calculated using the value for λ, ρ and c_p at ambient conditions (20 °C, 10% vol). See Annex for details.

Material	Lambda [W/mK]	Rho [kg/m^3]	C_p [J/kg.K]	b-factor [J/m^2.s$^{1/2}$.K]
Normal weight concrete	2,0	2.300,0	900,0	2.034,0
Light weight concrete	1,0	1.500,0	840,0	1.122,0
Middle weight concrete	1,0	2.000,0	840,0	1.296,0
Structural steel	54,0	7.850,0	425,0	13.422,0
Cerablanket	0,035	128,0	800,0	59,9
CaSi-board	0,069	450,0	748,0	151,9
Wood	0,1	450,0	1.113,0	223,0
Brick	1,0	2.000,0	1.114,0	1.521,0

Table 7-1 : Material properties at ambient conditions (20°C, 10% vol)

8 HEAT TRANSFER TO STRUCTURAL ELEMENTS

8.1 CONCEPT

Various models (see chapter 3) are available to calculate the temperature inside a compartment as a function of time. To know the temperature of the structural elements in function of time, it is necessary to calculate the heat flux to this element.

Convective and radiative heat transfer occur between the hot gases, the flame, the surrounding boundary constructions and the structural element. Emissivities and convection coefficients govern the heat transfer.

The heating up of a structural element depends on the type of element (e.g. pure steel or composite - steel / concrete) and of the nature and amount of fire protection.

8.2 HEAT FLUX

8.2.1 GENERAL

At a given time (t), during the fire, the heat flux to a surface is given by:

$$\dot{h}_{net} = \dot{h}_c + \dot{h}_r$$

The convective heat transfer is mainly a function of the gas movement around the structural element and is given by:

$$\dot{h}_c = \alpha_c (\theta_g - \theta_m)$$

where:

α_c	is the convection coefficient	($W/m^2/K$)
θ_g	is the gas temperature	(^oC)
θ_m	is the structural element temperature	(^oC)

The radiative heat transfer is generally given by:

$$\dot{h}_r = \phi \cdot \varepsilon_f \cdot \varepsilon_s \cdot \sigma \left[(\theta_g + 273)^4 - (\theta_m + 273)^4 \right]$$

where :

ε_f	emissivity of the fire compartment (gas+boundaries),
ε_s	emissivity of the structural element
θ_g	temperature of the gas (K)
θ_m	temperature of the structural element (K)
σ	Boltzmann constant
ϕ	view factor

Recently the 'plate thermocouple' has been accepted in Europe as a standard means of regulating the furnace in fire resistance testing. The 'plate' gives a much better indication of the actual thermal attack of the test specimens then the previously used thermocouples. In Annex C a short a explanation (including the physics of the heat transfer aspects for the plate) on this topic is given.

8.2.2 NOMINAL FIRES

$\varepsilon_f \cdot \varepsilon_s$

When dealing with nominal fires (i.e. standard or hydrocarbon), it is implicitly assumed that the structural element is located within a testing furnace. In this case the hot gases are rather transparent and consequently the emissivity of the furnace is about 0,8. If the emissivity of the structural element is 0,625 for unprotected steel, the effective emissivity is equal to 0,50 (values given in Eurocode 1 - part 2.2) (8.2). For concrete or fire protection material a value of 0,7 can be used for the emissivity. The effective emissivity is defined by $\varepsilon_f \cong \varepsilon_s = 0{,}56$. Regarding the convection, coefficients of 25 W/m². K for the standard fire and of 50 W/(m². K) for hydrocarbon fire are generally used.

8.2.3 "NATURAL" FIRES

In a real fire, other values for convection coefficients and emissivity of the compartment (wall + gas) can be expected. This is mainly due to the velocity of the gas, which will be higher than in a furnace. The emissivity of the gases will be higher than the values found in furnaces.
The properties of smoke and hot gas vary in time. Generally, hot gases have a large extinction coefficient at the beginning of the fire, and tend to become more transparent when the temperature is high and decrease again at the end of the fire.

From natural fire test results [8-1], some figures for heat transfer coefficients were assessed by considering the temperature recorded on unprotected steel sections. These values are given in Figure 8-1.

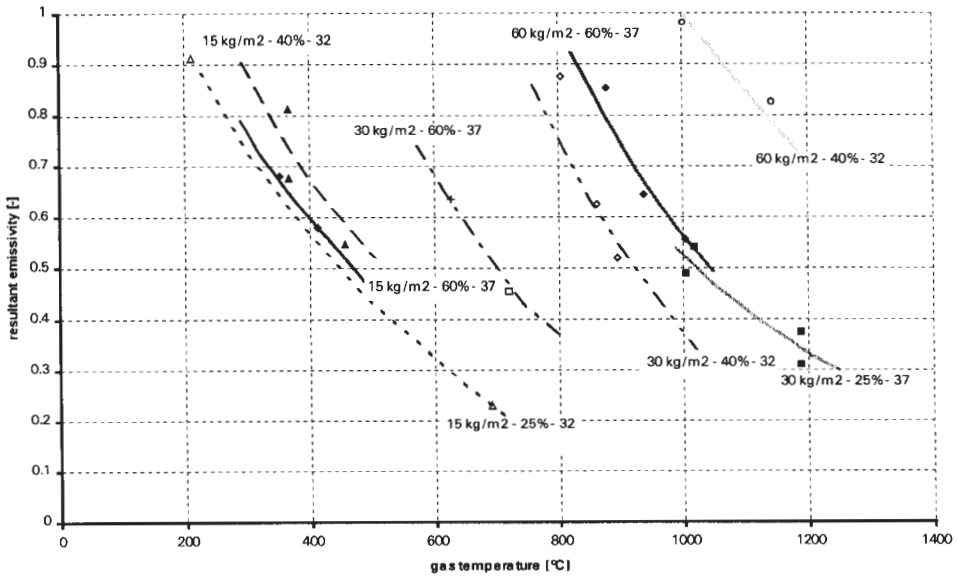


Figure 8-1: Values of resultant emissivities for various wood crib fires (fire load density and the percentage of opening in the front facade are given) The last number for each case is the convective heat transfer at 400°C.

8.3 CONCLUSION

For the design based on natural fires the following values are suggested for the heat transfer to structural elements:

Convection coefficient	35 $kW/m^2.K$
Emissivity of unprotected steel	0,625
Emissivity of the compartment	1

When rough methods are used to calculate the mechanical behaviour of structural elements (as critical temperature), the simple equations given above -assuming a uniform temperature in the fire compartment are sufficient. When a mechanical model calculates the mechanical behaviour of the structure (global structural calculations), a more accurate model has to be used to calculate the heat transfer to structural elements and to determine temperature gradients.

9 DESIGN GUIDANCE

9.1 INTRODUCTION

In the "Natural Fire Safety" approach the fire safety design is based on physically determined thermal actions. In contrast with the conventional design, parameters like fire load, rate of heat release and the amount of ventilation play an important role in the natural fire design. The specification of appropriate design fire scenarios (i.e. the course of a fire with respect to time and space) is a crucial aspect of fire safety design. The assumptions made with regard to these factors have major influence on the conditions in the compartment and have significant impact on the fire design.

The design fire scenarios used for the analysis/development of a building fire have to be deduced from all the possible fire scenarios. In most buildings the number of possible fire scenarios is infinite and need to be reduced to enable analysis and calculation. If the design fire scenarios are chosen, a number of fire models is available to calculate the thermal actions. For detailed information on the various calculation models, see the report of Working Group 1 "Fire Models".

The work of Working Group 3 "Fire Characteristics" is to supply the input data and to supply ready-to use guidance on these data for the Natural Fire Design.
The results of the work are in this report. This chapter is a summary of the operational information. Three example calculations are included, explaining the proposed Natural Fire Safety approach. For details refer to the previous chapters and to the work of the other Working Groups.

9.2 THE FIRE SCENARIO

The starting point for calculating thermal actions (modelling) is the fire. The fire (scenario) depends on the ignition source, the amount and type of fuel, the ventilation, the growth rate, the rate of heat release etc. The fire scenario (RHR, duration of the fire) is summarised in chapter 5. See more particularly Figure 5.7.

9.3 THE ENCLOSURE

For the spread of fire in a building it is important to know the behaviour of boundary elements of the enclosure where the fire started under natural fire conditions (walls, doors, windows).

9.3.1 BOUNDARY ELEMENTS

The behaviour of boundary elements can be assessed by:

- Ad-hoc tests
  The element can be exposed to a temperature-time curve in a furnace, as calculated with fire models based on the worst-case fire scenarios. Basic problems are:
  - the worst case scenario is a priory not known;
  - the number of fire tests needed is very large.

- Expert judgement
  This approach makes use of the available test-data of ISO-resistance tests on separating elements. In combination with calculation procedures, the behaviour under natural fire conditions can be assessed for a limited number of simple elements (e.g. monolite walls). For more complex wall constructions this approach is not feasible.
- Direct use of ISO-requirements
  National rules require a certain ISO-fire resistance of walls and floors, depending on their use and geometry. Direct use of ISO-requirements is based on the following assumption: a fire will not grow beyond the fire compartment, if the boundaries are fulfilling these national rules.
  If the fire starts in an enclosure within a fire compartment the fire will stay in the enclosure for 15 minutes and after that the fire compartment is progressively involved. This is a rough but easy approach.

The first two options can be used for a limited number of separating elements, and will lead to high costs. In practise, often the 3rd option has to be used.

9.3.2 OPENING (WINDOWS, GLAZING, DOORS, EXTRACTION VENTILATORS)

Openings in an enclosure can consist of windows, doors and roof vents. The severity of the fire in an enclosure depends on the amount of openings in the enclosure. The following rules are proposed:

- Doors are assumed to be closed if the enclosure has other openings.
- Doors are assumed to be opened if the enclosure has no other openings.
- Glazing without fire rating is broken from the start of the fire. If the size of the window/glazing in a certain wall is higher than 50% of the total surface of that wall surface, only 50% of that wall surface is assumed to be broken; (upper part of the glazing/wall). This assumption is based on the notion that normal glass will break at relative low temperatures. In Annexe D this assumption is explained theoretically.
- For glazing with a fire rating, the same approach as with separating elements can be used (adhoc, expert or direct use ISO-requirements).
- Simple models can use the so-called opening factor to model the openings in an enclosure. More complex models can use a flow calculation based on the actual flow through an opening.
- The opening factor can be calculated for enclosures with one vertical opening, with multiple vertical openings and with a combination of horizontal and vertical openings. Complex models (solving mass/heat balance equations) are also available (e.g. OZONE).

The heat in an enclosure can be lost from the enclosure by radiation and by convection. The convection part can be calculated with a simple model (using the opening factor) or complex models (solving mass/heat balance equations).

The heat loss to the walls of the enclosure may be neglected, but this will lead to conservative outcomes. Both a simple thermal-inertia approach and more sophisticated models are readily available to quantify the effect.

9.4 DESIGN EXAMPLES OF THE APPLICATION OF THE NFSC APPROACH

In this paragraph three examples are given to show the application of the Natural Fire Safety Concept in the design of 'real' buildings.

The first example introduces the design of a new Hospital in Esch-sur-Alzette. In this example fully engulfed fires are expected, and the goal of the calculations is to decide on the necessary level of protection for the steel construction in the building.

The second example is about the design of a large industrial hall in France. Due to the amount and storage of the combustible goods, the fire remains localised. The goal of the calculations is to evaluate the necessary amount of smoke ventilation to prevent damage to the steel beams in the roof of the building, and to maintain a smoke free zone at floor level for the fire fighters.

The third example is based on the redesign of a single story shopping mall in the Netherlands. The basic idea is that the (small) shops in the current situation are individual fire compartments with fire resistant separating elements. The roof of the mall is fitted with natural smoke ventilators. All shops have one opening (entrance) to the mall, that is not fire resistant.

Renewal plans have been proposed in which several small shops are combined into a number of larger shops. The goal of the calculations was to decide if this combination of shops would require extra fire safety measures, i.e. large smoke ventilators or fire protection of the previous unprotected steel structure in the mall.

9.4.1 EXAMPLE 1: "HOSPITAL ESCH-SUR-ALZETTE"

One fire compartment of the Hospital was studied. This fire compartment consists of a number of hospital bedrooms, and a connecting corridor. In the figure the plan of the fire compartment in the hospital that was studied is drawn.

After analyzing the situation three credible worst-case scenarios have been selected. The three scenarios correspond to a fully engulfed fire enclosure, with varying size and opening factor of this enclosure, thus resulting in different conditions in the enclosure for the steel structure.

- a fire restricted to one bedroom (door is closed);
- a fire that spreads from one bedroom to the corridor also involving the small rooms in the middle of the corridor, and
- a fire that involves the complete fire compartment.

These three scenario's have been calculated with the one-zone model "OZONE" , that was developed in the scope of this NFSC project.

The goal of the calculations was to determine the necessary amount of protection for the steel construction, including the option of unprotected steel.

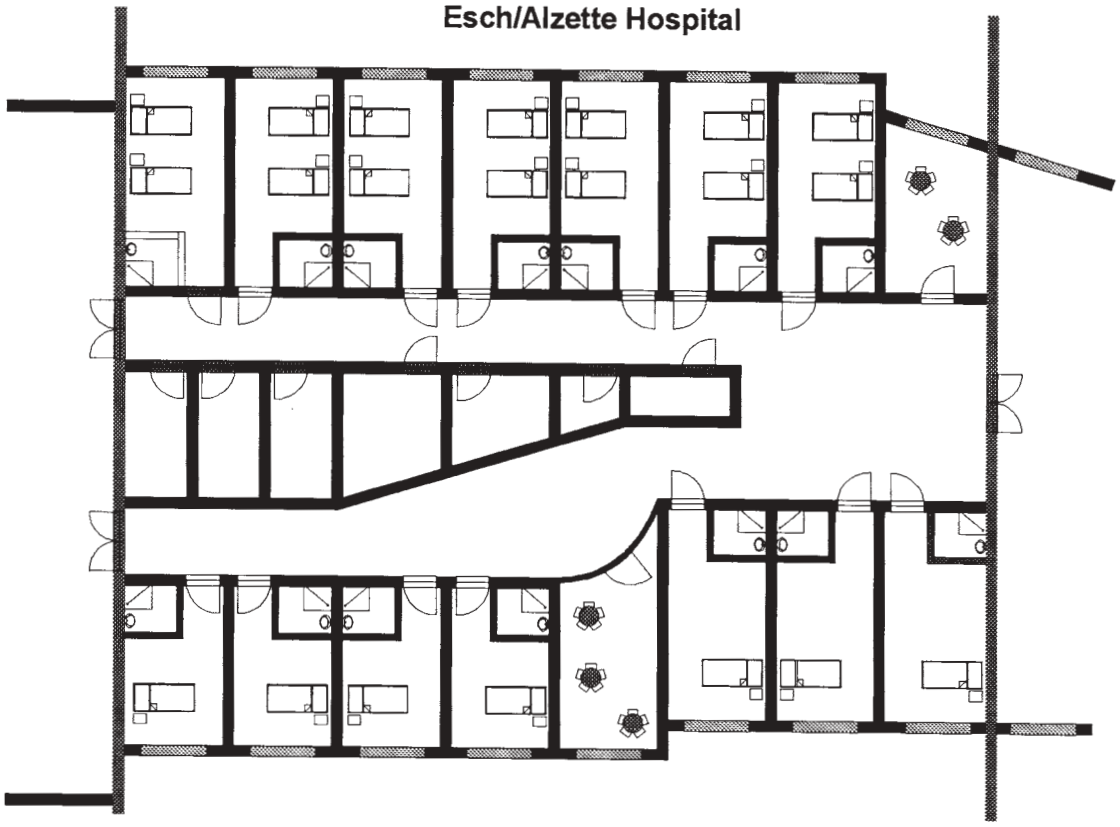
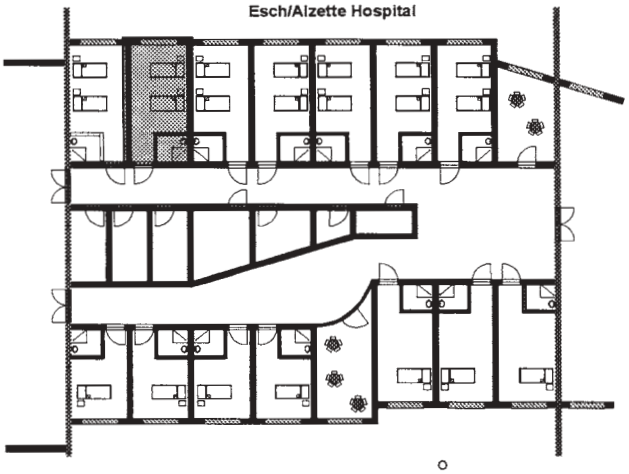
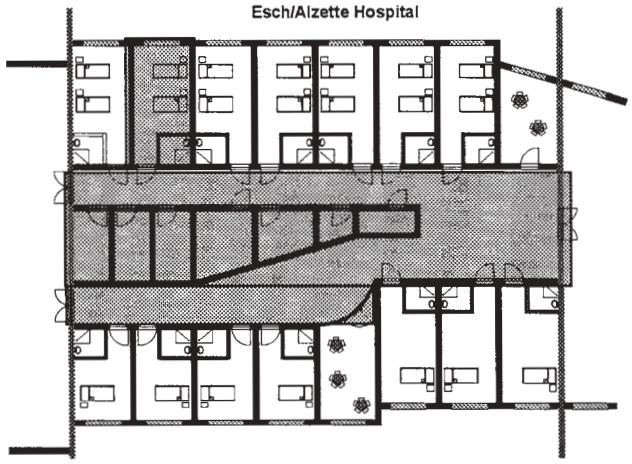


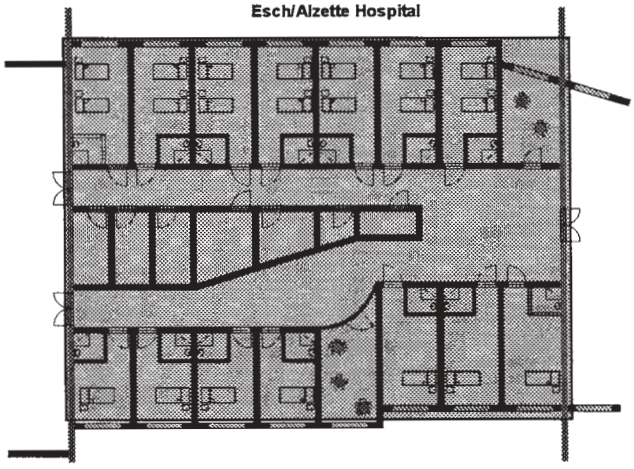
Figure 9-1: Plan of the fire compartment in the hospital, which was studied.



Case 1:
Fire enclosure consists of one large hospital bedroom with 2 beds with an area: 26 m²; 1 window/opening: 2,20 x 2,30 m ≅ 5 m², corresponding to the window completely broken by the heat.



Case 2:
Fire enclosure consists of one large bedroom, the corridor and all small rooms in the corridor with an area: 284 m²;
1 opening: 2,20 x 2,30 m ≅ 5 m², corresponding to the window of one room supposed completely broken by the heat.



Case 3:
The fire enclosure consists of the whole compartment on the 1st floor with an area: 672 m²; 1 opening: 16 x 5 m² = 80 m², corresponding to all the windows supposed completely broken by the heat.

Figure 9-2: Schematic view of the three cases (fire compartment in gray).

Design fire

For the three scenarios, the following assumptions have been considered:

Fire growth rate:

The hospital is not in the tables in this report, but can be compared with a hotel bedroom resulting in a moderate growth rate of the rate of heat release RHR:

$$RHR(t) = \left(\frac{t}{t_\alpha}\right)^2 \quad [MW] \quad \text{with } t_\alpha = 300 \text{ sec}$$

Rate of heat release per m^2 floor area (steady-state until 70% of the fire load is consumed):

The hospital is compared with an office building resulting in:

$RHR_f = 250\ kW/m^2$

Rate of heat release in the decay phase:

Linear decrease of the RHR until all entire fire load is consumed.

Design fire load $q_{d,f}$: (subvalues for various parameters can be found in the complete NFSC final report)

$q_{d,f} = m * q_{k,f} * \gamma_{q1} * \gamma_{q2} * \gamma_{n1} * \gamma_{n2} * \gamma_{n3}$

Characteristic fire load: $q_{k,f} = 350$ MJ/m² (80% fractile for hospital: table 4-3)

A value $q_{k,f} = 350$ MJ/m² (different from the value 280 MJ/m² of the table 4-3) was used in the examples, based on a coarse analysis of the data on fire load densities.

Fire Activation Danger: depending on compartment size; hence γ_{q1} = 1,05; 1,3 and 1,35 for the three cases.

Fire Activation Danger depending on occupation type (hospital); hence $\gamma_{q2} = 1,0$

Automatic smoke detection: hence $\gamma_{n1} = 0,8$

Automatic Alarm Transmission Fire brigade, hence $\gamma_{n2} = 0,9$

Fire Fighting Measures: only off site fire brigade, hence $\gamma_{n2} = 0,73$

The three scenarios are described in table 9-1. Together with the calculated maximum temperature in the critical steel component (unprotected steel element with a section factor of 143 m^{-1})

Scenario	γ_{q1}	q_{df} (MJ/m^2)	Fire area (m2)	Opening (m^2)	$\theta_{steel\ max}$
Case 1	1,05	195	26	5	**420**
Case 2	1,3	242	284	5	**431**
Case 3	1,35	252	672	80	**610**

Table 9-1: The three scenarios (input data and results)

The analysis of the previous scenarios (1, 2 and 3) points out that the scenario 3 is the most unfavourable for the steel structure, this case should be considered in the thermo-mechanical simulation of the structure. For details refer to Figures 9-3, 9-4 and 9-5.

Conclusion: for the load level of this hospital the steel structure may remain unprotected.

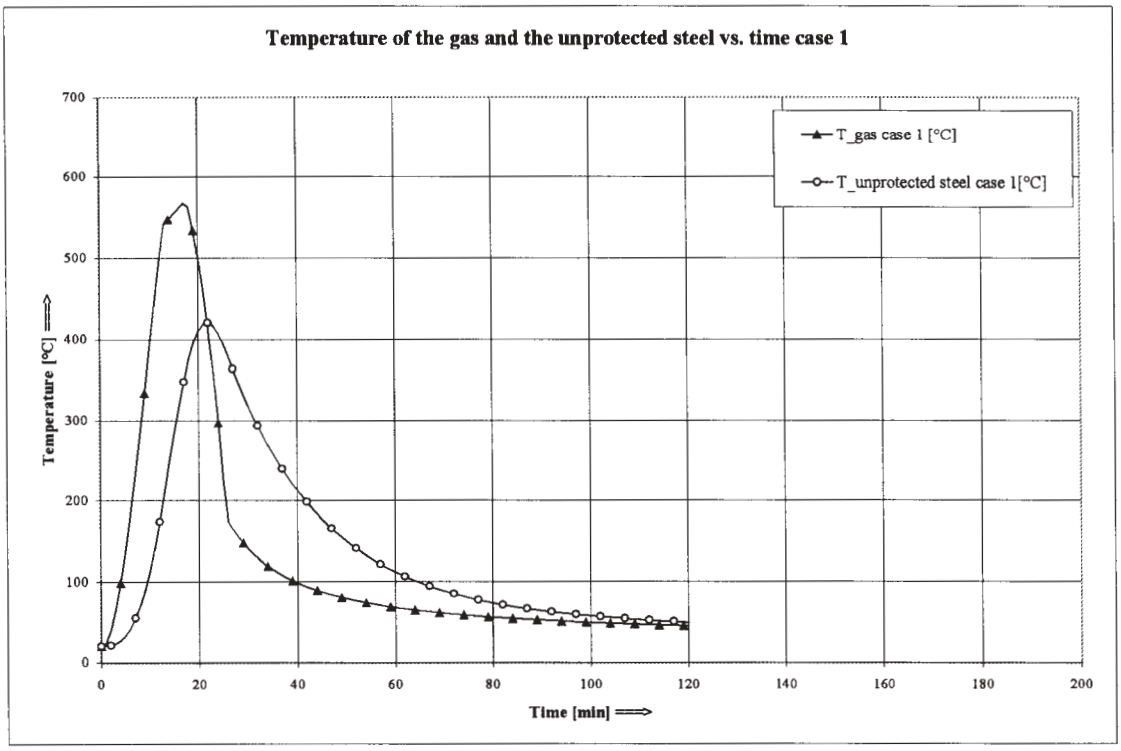


Figure 9-3: Temperature of the gas and the unprotected steel vs. time for case 1. Hospital Esch/Alzette.

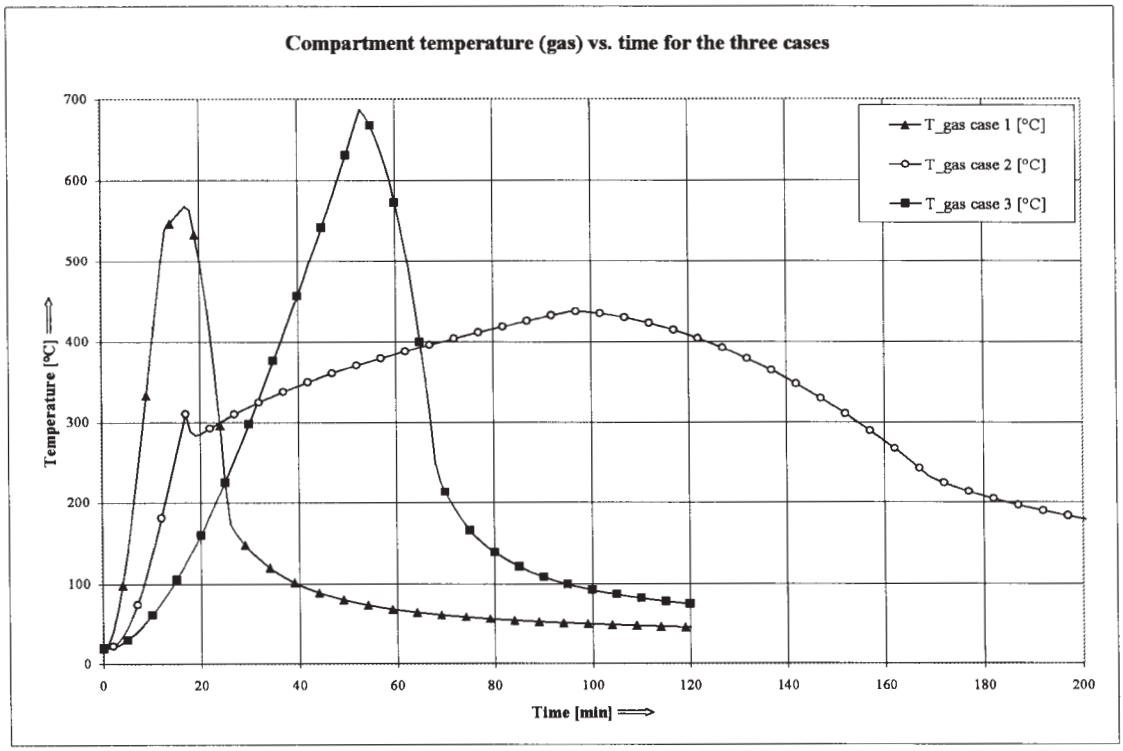


Figure 9-4: Compartment temperature (gas) vs. time for the three cases. Hospital Esch/Alzette.

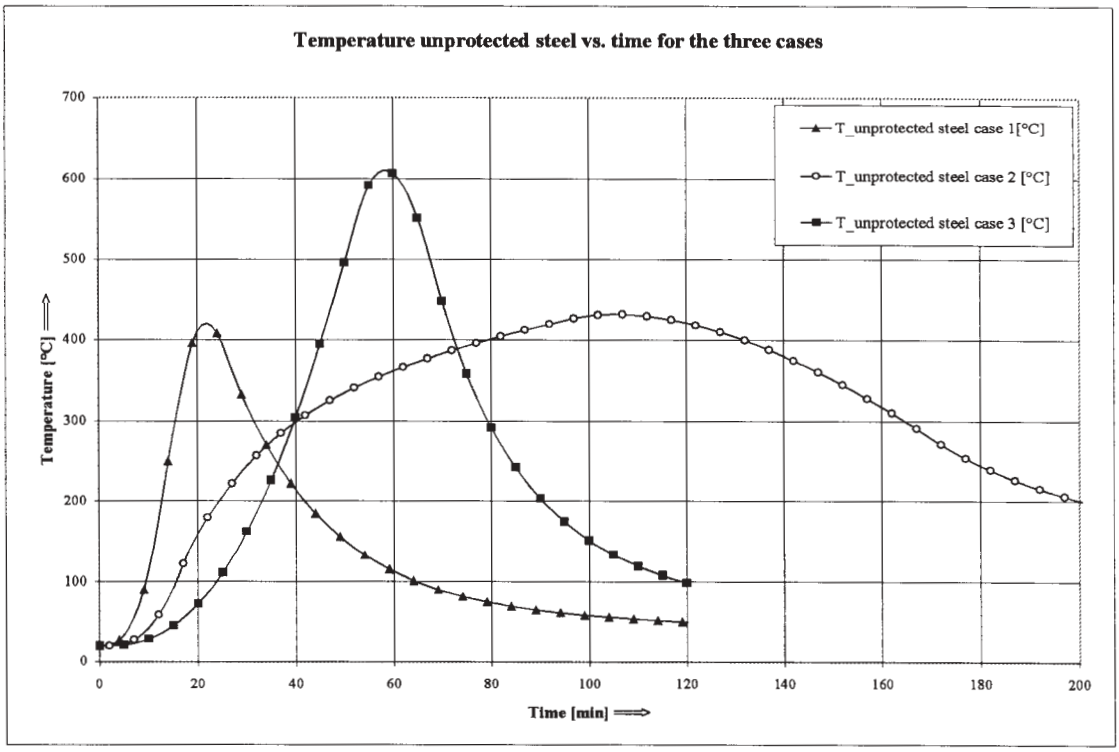


Figure 9-5: Temperature unprotected steel vs. time for the three cases. Hospital Esch/Alzette.

9.4.2 EXAMPLE 2: "INDUSTRIAL HALL"

In an industrial building 15 x 200 x 7 (= width x depth x height) containing a large fire load, a fully engulfed fire implies a structural failure of the building if insufficient protection of the steel structure is used.

The first objective is the safe evacuation of occupants and the second is to avoid a fully developed fire in the building.

To reach these objectives, the fire has to be limited, and smoke evacuation has to allow the evacuation of people and to allow the fire brigade to attack the fire.

The spread of fire is limited by storing the goods in 'islands', separated by zones that are free of combustibles. The smoke evacuation is used to limit the temperature in the hot smoke layer under the roof, thus preventing the ignition -by radiation from the hot layer- of other 'islands' of combustibles.
The maximum height of the stacked combustibles is 3,5 m. This implies that the smoke-free zone should at least have a thickness of 4 m to prevent ignition of combustibles by convection from the hot gas layer.

In this approach, the development of the temperature and the thickness of the hot gas layer have to be studied.

A two-zone model (CFAST) is used in order to estimate the temperature and the thickness vs. time of the hot layer for three cases with varying smoke extraction capacity.
Fire compartment dimensions:

- compartment walls:
  sandwich construction steel 1 mm/insulation 20 mm/steel 1 mm
- fire:
  =medium fire growth rate according to Table 5.2
  =RHR per m^2 floor area = 500 kW/m^2 (value of Table 5.2).
  =the steady state situation (RHR_{max} = 9 MW) is reached because the size of the 'islands' of combustibles, separated by areas free of combustibles is limited to 18 m^2. Furthermore the fire brigade will arrive well within 15 minutes after detection of the fire, limiting any further spread of fire if a smoke free zone is maintained until the fire brigade arrives.

Natural ventilation. Three cases are simulated:

- Case 1:
  - vents: 6 vents with a surface of 5 m^2
  - vertical openings: 3 openings on the floor with 3 m high and 4 m width
- Case 2:
  - vents: 2 vents with a surface of 5 m^2
  - vertical opening: 3 openings on the floor with 3 m high and 2 m width
- Case 3:
  - vertical opening: 3 openings on the floor with 3 m high and 4 m width.

According to these data, calculations with two zone models may be applied. The results of simulation with CFAST are shown. Figure 9-6 shows the temperature of the hot layer and Figure 10-2 the height of the hot gas layer for the three cases.

Conclusion Industrial Hall:
Case 3:
In case 3 the height of the smoke free zone is not large enough; the combustibles will be in the hot layer. Since the temperature of the hot gas layer is higher then 150 °C, the ignition of secondary fires by convection (to other 'islands' of combustibles) in the hall can not be prevented, so the spread of fire is not limited thus resulting in a fully involved fire $\Rightarrow$ not acceptable.

Case 1 and 2:
In these cases the height of the smoke free zone is large enough to prevent spread of fire by convection (no combustibles in the smoke layer). The temperature in the hot gas layer is low; spread of fire due to radiation from the hot gas layer is therefore not expected. To prevent ignition of other 'islands' of combustibles by direct radiation from the fire, the distance between these islands should be large enough. For this aspect the quick arrival of the fire brigade should be taken into account.

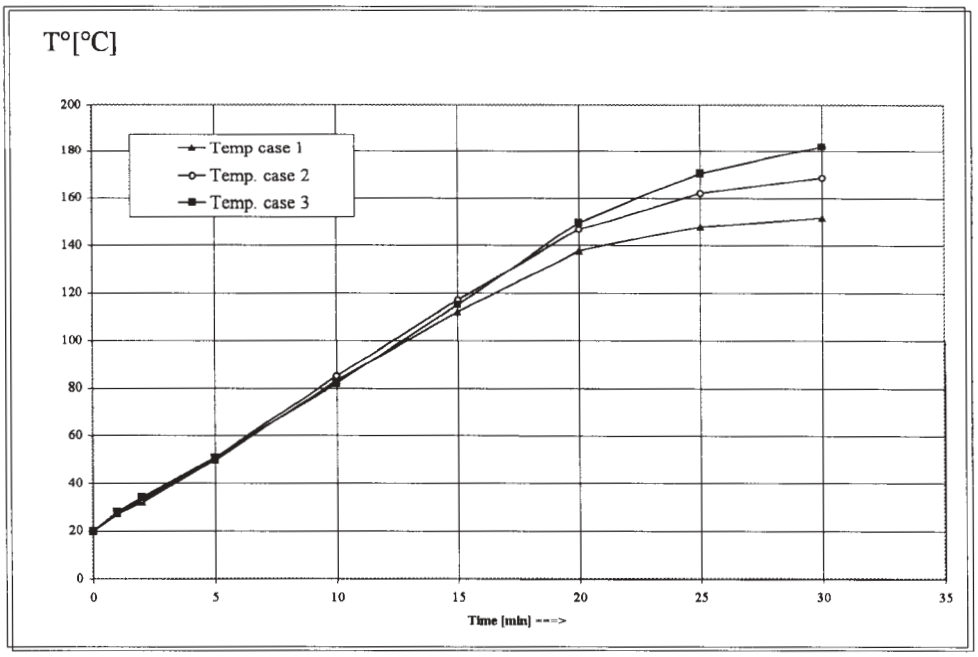


Figure 9-6: Temperature of the 'hot' zone in the three cases. Industrial Hall.

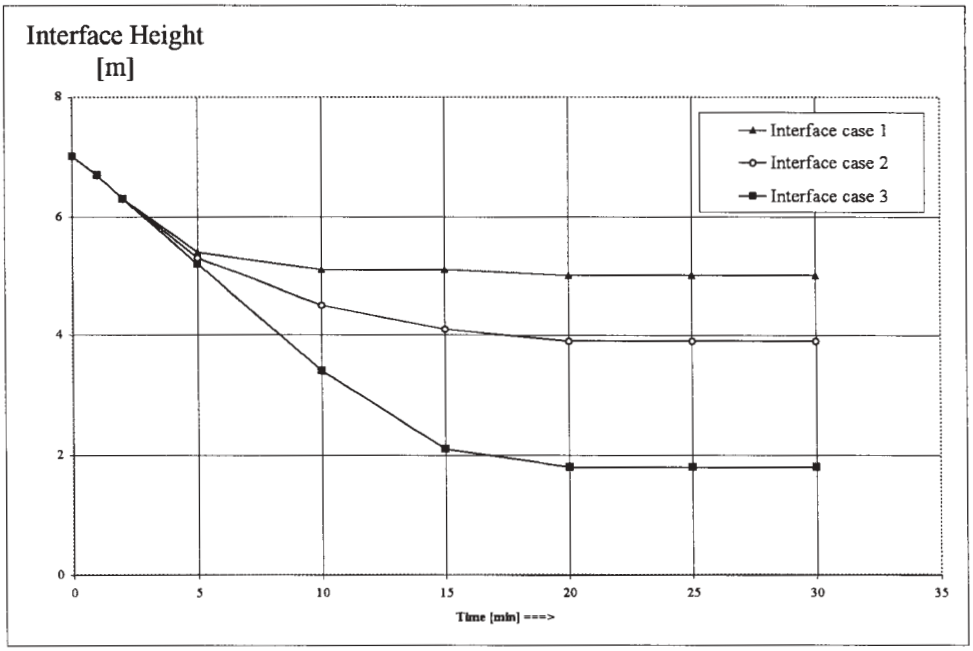


Figure 9-7: Interface height in the three cases. Indutrial Hall.

9.4.3 EXAMPLE 3: "SHOPPING MALL"

Description of the building

The building is a shopping mall with shops on ground level, which are connected with a mall. The roof of the mall is at a height of 13 m, while the height of the shops is 4 m. The floor area of the mall has a surface of 1300 m^2. Fire resistant walls separate the shops. The mall is fitted with a natural smoke ventilation system, consisting of 20 m^2 ventilators, and 20 m^2 openings on ground level.

Renewal plans have been proposed in which several small shops (area ~ 25 m^2) will be combined into a number of larger shops. The goal of the calculations is to decide if this combination of shops would require extra fire safety measures, e.g. larger capacity of the smoke extraction in the mall.

The basic assumption is that a fire will start in a shop, and the smoke will flow into the mall through the opening. The fire will grow to flashover in the shop.

Calculations are made of the smoke temperature in the mall as a function of time. The height of the smoke free zone in the mall is also calculated.

Three cases are calculated with varying size of the shop 25, 100 and 200 m^2 (corresponding to the combination of 1, 4 or 8 small shops). The main interest of this example is in the temperature of the smoke in the mall. After the growth phase a steady state situation occurs when the shop is completely involved in fire.

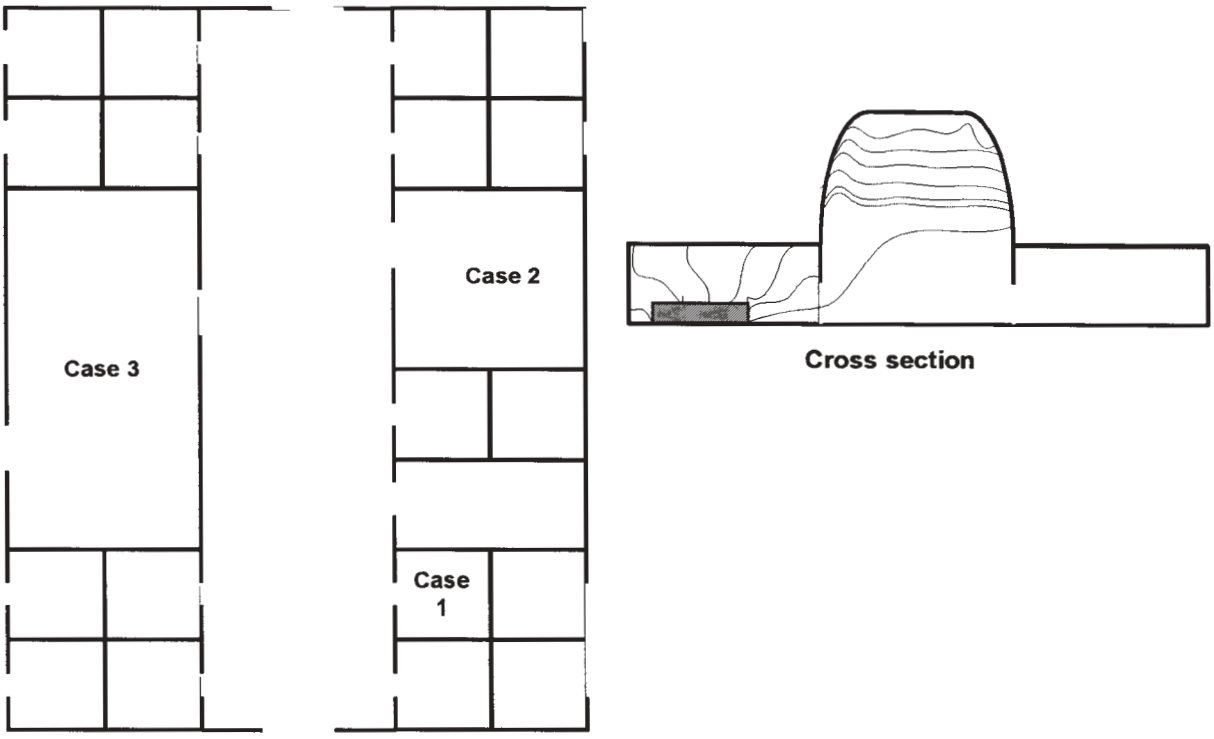


Figure 9-8: Plan of the shopping mall.

Calculation model and input

The calculations are performed with a two-zone model [9-1]. For this example the actual conditions in the shop are of no interest, since fire resistant walls separate the shop. Only the amount of heat and smoke flowing into the mall is relevant. As a save assumption the heat loss to the walls of the shop is not used in the calculation.

The RHR per floor area for retail function is:

$RHR_f = 500\ kW/m^2$

$RHR = \left(\frac{t}{t_\alpha}\right)^2$ [MW] until RHR = RHR_{max} (complete shop involved)

With propagation factor: t_α = 150 sec.

t_α is the fire growth rate = time to reach a RHR of 1 MW

Case 1: = shop area of 25 m^2
Case 2: = shop area of 100 m^2
Case 3: = shop area of 200 m^2

In all cases the opening to mall consist of one opened door = 2*2,5 (w*h).
In the Figures. 9-9 and 9-10 the temperature of the smoke in the mall and the height of the smoke free zone is given as a function of time for the three cases.

Conclusion:

The calculations show that no extra fire safety measures are necessary if the maximum size of combined shops is not larger than 100 m^2 (case 2).

The temperature in the hot smoke layer for that case is well below 200 °C. The radiation from the smoke layer will not prevent a safe escape of the public at the ground level. The height of the smoke zone is well above 2,5 m, which is the required value for escape of the public. The temperatures in the smoke layer are so low that the steel structure in the mall does not have to be protected.

If larger shops will be made, extra fire safety measures should be taken. In this case extra smoke ventilators and openings could be installed; if for some reason this is not possible a sprinkler installation could be installed.

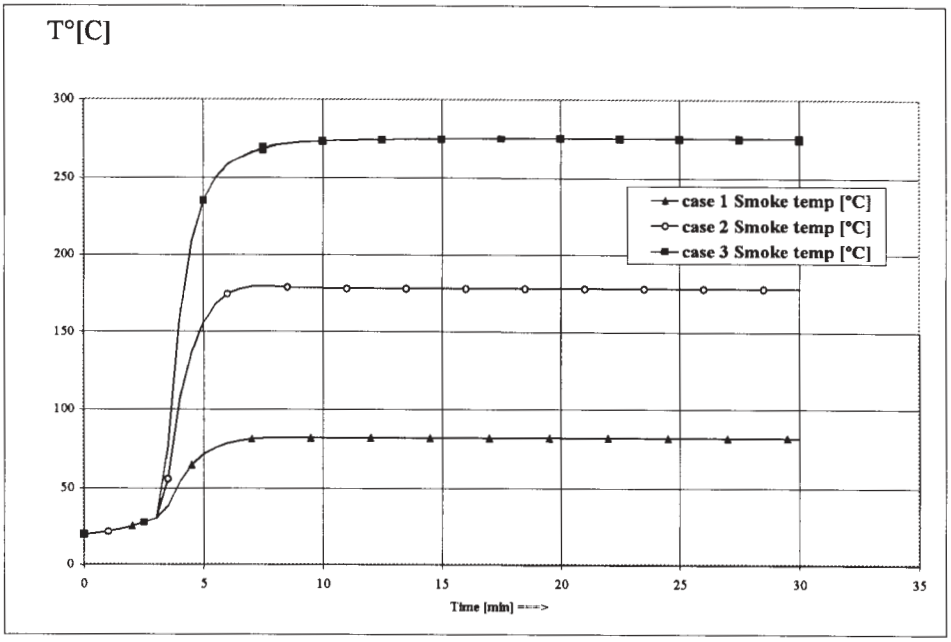


Figure 9-9: Temperature development of the hot zone for the three cases. Shopping mall.

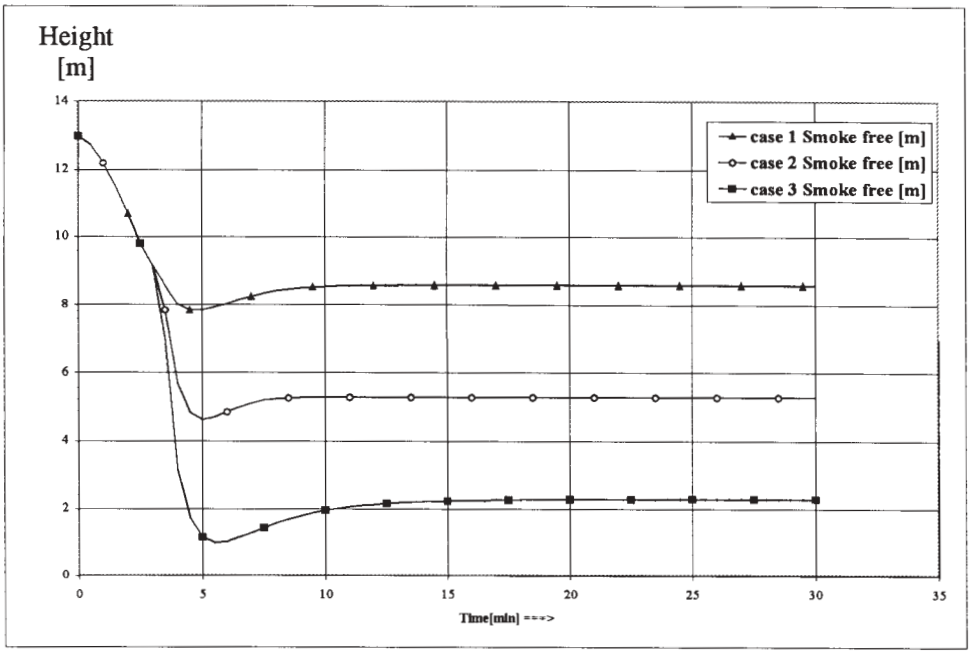


Figure 9-10: Temperature development of the hot zone for the three cases. Shopping mall.

10 APPENDIX A: DATA ON THERMAL PROPERTIES AT ELEVATED TEMPERATURES; USED IN THE BOUNDARY ELEMENTS

Introduction

In Table A.1 the relevant values for material properties are given for a number of common building and insulating materials. Included is the penetration depth, a measure for the penetration of heat into the wall. In calculating the heat flux into the wall with sufficient accuracy (~ 5 %) the theory can be used for materials with a thickness greater than, or equal to the penetration depth.

The value of the penetration depth in Table A.1 is calculated with the assumption of a heating period (fire duration) of one hour in the fire room, and a high convection coefficient for the heat transfer to the walls. For building materials like concrete and brick of normal thickness the criterion is easily met. No large errors can be expected by using the thermal inertia approach, in such situations.

For insulated walls (sandwich constructions) this is not always true. The error introduced by using this approach can be assessed by calculating the heat-flux into the wall by using a computational model for a number of walls with different kind and thickness of insulating materials.

Eurocode 1: sandwich constructions

A very common type of wall in buildings consists of a sandwich construction of various materials, each with its own "thermal inertia" (b-factor).

In Eurocode 1 the following approach using an effective b-factor is suggested, to account for walls/enclosures with layers of different materials. The procedure is to be used only for b factors between 1.000 and 2.000 [J / m^2 $s^{0,5}$ K]

$$\text{b-factor} = \sqrt{\sum_i (s_i \cdot c_i \cdot \lambda_i) / \sum_i (s_i \cdot c_i \cdot \lambda_i / b_i^2)}$$

where:

λ_i = heat conductivity of material i, in W/(m.K)
s_i = thickness of material i, in m
c_i = heat capacity of material i in J/(kg.K)
b_i = b-factor of material i, in J/(m2√s.K)

As explained in the main text, from a point of view of logic and physics there are some obvious shortcomings to this rule. To assess the effect of this rule of thumb - both inside and outside of the application range given in the Eurocode 1- calculations have been carried out on 25 different sandwich constructions that are used in building practice. The results are given in the next paragraph.

Calculations (basic idea)

With the FEM and FD computer models available at TNO (Heat-1D and DIANA) a number of calculations has been carried out. Objective was to compare the above mentioned Eurocode 1 'rule-of-thumb' for determination of the effective b-factor of sandwich materials with 'reality'. Calculations have been performed for two-layer sandwich constructions. For each of the material combinations, five different thicknesses of the first (heated) layer were calculated.

In the calculations the heated side of the construction was forced to a temperature 600 °C at t=0. The total heat lost to the wall was calculated as a function of time.
To translate this result into terms of b-factors, a corresponding homogenous material is deduced (penetration theory) that would have taken up the same amount of heat as the tested construction after 60 minutes. Arbitrarily the value at t = 60 minutes is chosen. Most fires of interest will last at least this long. It can be seen that this approach leads to safe answers; if the fire lasts longer, more heat will flow into the walls than calculated. In Figure A.1 this approach is illustrated.

Calculations (Calculation vs. Eurocode 1)

With the above-mentioned procedure the effective b-factor of sandwich materials was calculated for 5 material combinations and five thicknesses of the first (heated) layer, i.e. 5, 10, 20, 50 and 100 mm. The sandwich constructions consist of materials with the following b-factors. The material properties (λ, ρ and C_p) were chosen to reassemble building materials in practice.

50	very good isolation (e.g. ceramic wool)
200	good insulator (e.g. CaCi board)
1.000	LWC (Light weight concrete)
2.000	NWC (normal weight concrete)
15.000	normal steel.

The sandwich constructions were calculated for a number of material combinations. The thickness of the first (direct exposed) layer was varied for each material combination. The thickness of the second material has been chosen 200 mm for all calculations. The Eurocode rule is restricted to b-factors between 1.000 and 2.000 $J/\left(m^2 \cdot K \cdot \sqrt{s}\right)$.

Combinations:

a NWC insulated with ceramic wool
b NWC insulated with CaSi
c NWC 'insulated' with LWC
d LWC insulated with Promatect
e LWC 'insulated' with NWC

In Figure A-2 the results are given for both the calculations (a,b,c,d) and the EC1 approach. In the figure the black columns represent the EC1 values, the light columns are the calculation results.

The results are grouped with respect to material combination. That means the first five lines give the results for combination a; from left to right for growing thicknesses of the first (heated) material. The thickness used is 5,10,20,50 and 100 mm.

From this figure can be seen that the EC1 approach largely overestimates the effective b-factor in case of insulated materials. This leads to an overestimate of the total heat lost to the walls. In a natural fire safety concept this leads to unsafe results.

Conclusion

Use of the EC1 rule for calculating effective b-factors is not recommended. Within the application range (materials with a b-factor between 1.000 and 2.000) the rule is not a safe approach, but the overestimation of the effective b-factor (unsafe) is limited to approximately 50%. For materials with b-factors outside the range 1.000-2.000 the effective b-factor can be over estimated by a factor 3. This leads to very unsafe results shown in Figure 7-1.

For the time being, as a safe approach for calculating the effective b-factor for sandwich constructions, the smallest b-factor of the materials in the sandwich construction should be used.

In the figure the grey lines give the b-factor using this rule of thumb for the NFSC project.

For specific material combinations the approach proposed by working group 1: "fire modelling" of this project can be used.

file : d:\jur\nfsc\material.xls								
Material	temp	Lambda	Rho	Cp	sqrt(l*r*cp)	l/(r*cp) [m2/s]	Penetration depth	reference
	[°C]	[W/mK]	[kg/m3]	[J/kgK]			for t=3600 s [m]	
Normal weight concrete								ENV 1994-1-2 (EC4)
	20	2	2300	900	2034.70	9.66E-07	0.10	
	200	1.63	2300	1022	1957.42	6.93E-07	0.09	
	500	1.21	2300	1164	1799.84	4.52E-07	0.07	
	1000	0.83	2300	1289	1568.66	2.80E-07	0.06	
Light weight concrete (1500 kg/m3)								ENV 1994-1-2 (EC4)
	20	1	1500	840	1122.50	7.94E-07	0.09	
	200	0.875	1500	840	1050.00	6.94E-07	0.09	
	500	0.6875	1500	840	930.73	5.46E-07	0.08	
	1000	0.5	1500	840	793.73	3.97E-07	0.07	
Light weight concrete (2000 kg/m3)								ENV 1994-1-2 (EC4)
	20	1	2000	840	1296.15	5.95E-07	0.08	
	200	0.875	2000	840	1212.44	5.21E-07	0.08	
	500	0.6875	2000	840	1074.71	4.09E-07	0.07	
	1000	0.5	2000	840	916.52	2.98E-07	0.06	
Structural steel								ENV 1994-1-2 (EC4)
	20	54	7850	425	13422.28	1.62E-05	0.43	
	200	47	7850	530	13983.69	1.13E-05	0.36	
	500	37	7850	667	13918.70	7.07E-06	0.28	
	1000	27	7850	650	11737.44	5.29E-06	0.24	
Cerablanket (25 mm / 128 kg/m3)								RPS 19/92 ECSC-SA509
	20	0.035	128	800	59.87	3.42E-07	0.06	
	200	0.06	128	900	83.14	5.21E-07	0.08	
	500	0.12	128	1050	127.00	8.93E-07	0.10	
	1000	0.27	128	1100	194.98	1.92E-06	0.15	
Sealing cement no:1	20	0.0483	200	751	85.17	3.22E-07	0.06	Heat-1D database
	250	0.0681	200	954	113.99	3.57E-07	0.06	
	500	0.1128	200	1052	154.06	5.36E-07	0.08	
	800	0.2016	200	1059	206.64	9.52E-07	0.10	
CaCi board no:3	20	0.0685	450	748	151.85	2.04E-07	0.05	Heat-1D database
	250	0.0786	450	956	183.89	1.83E-07	0.05	
	450	0.0951	450	1060	212.99	1.99E-07	0.05	
	1050	0.157	450	1440	318.96	2.42E-07	0.05	
Wood (450 kg/m3)	20	0.1	450	1113	223.80	2.00E-07	0.05	Landbolt
	250	0.1	450	1125	225.00	1.98E-07	0.05	
	450	0.1	450	1135	226.00	1.96E-07	0.05	
	1050	0.1	450	1164	228.87	1.91E-07	0.05	
Brick	20	1.04	2000	1113	1521.53	4.67E-07	0.07	Landbolt
	200	1.04	2000	1125	1529.71	4.62E-07	0.07	
	500	1.18	2000	1135	1636.64	5.20E-07	0.08	
	1000	1.41	2000	1164	1811.76	6.06E-07	0.08	

Table A-1: Data on the thermal properties of different materials: temperature dependency of λ, ρ and C_p.

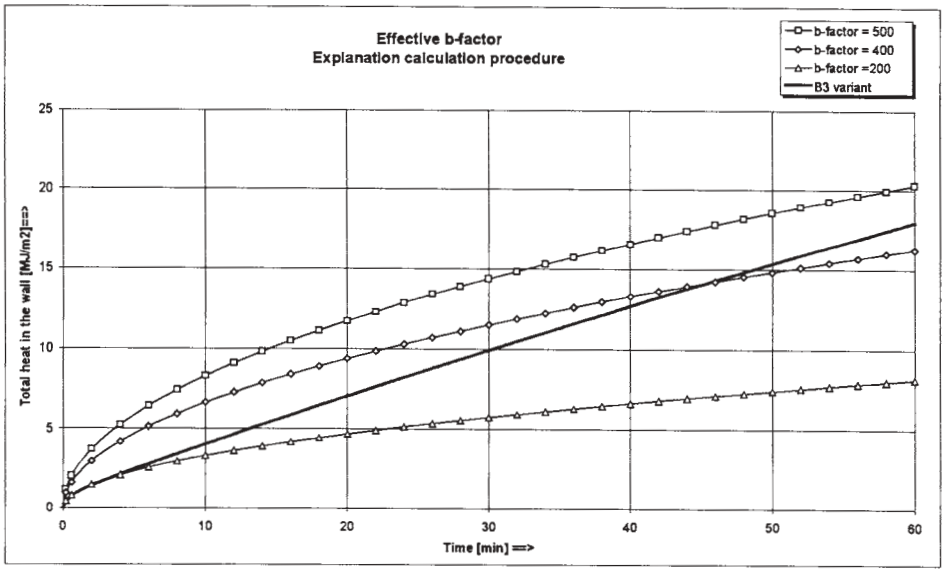


Figure A-1: Illustration of the calculation of an 'effective' b factor for sandwich materials.

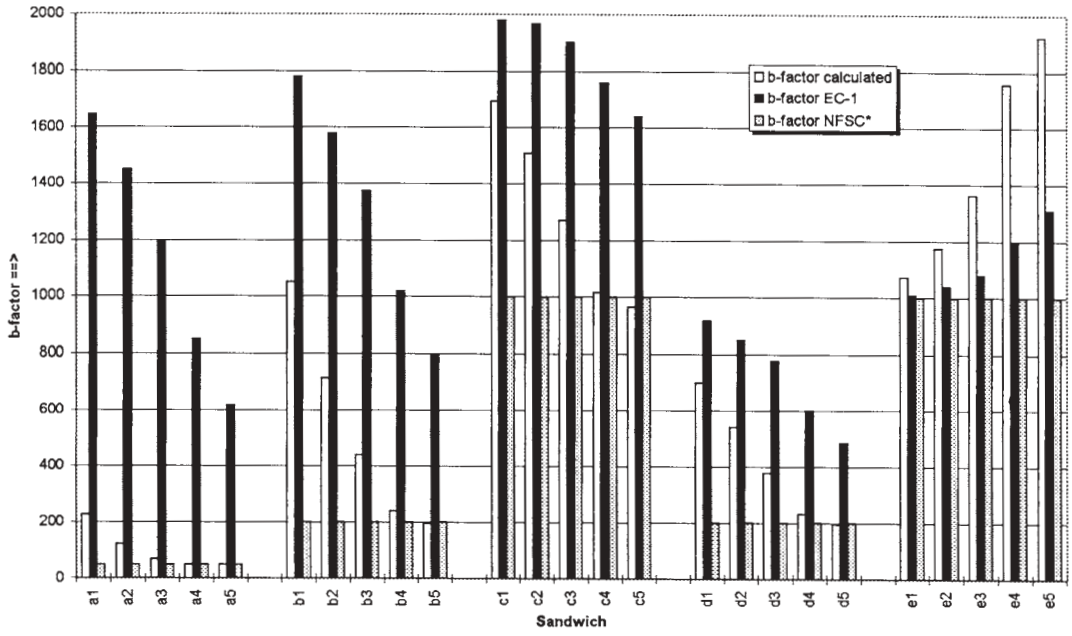


Figure A-2: Comparison between effective b-factors calculated with EC1 and calculated theoretically and the 'rule of thumb' proposed for the NFSC project.

11 APPENDIX B: THEORETICAL BACKGROUND OF THE "OPENING FACTOR" CONCEPT

The theoretical aspect can be described when we consider small openings and a small compartment having a homogeneous temperature (application case of a One Zone model).

With H the height of the opening, h_b the height under the neutral axis and h_a the height above the neutral axis ($h_a + h_b = H$), then the velocity of air entrance is described by Bernoulli:

$$\frac{\rho_o V_o^2}{2g} = h_b(\rho_i - \rho_e) \qquad \text{(B-1)}$$

Integrating on the entrance surface with a contraction factor « a » and
W the opening width, the quantity of air which entries in the compartment is

$$M = \frac{2}{3} a \rho_i h_b W \sqrt{2 g h_b (1 - \rho_i / \rho_e)} \qquad \text{(B-2)}$$

In the same manner the extraction M' for combustion products is deduced:

$$M' = \frac{2}{3} a \rho_i h_a W \sqrt{2 g h_a (\rho_e / \rho_i - 1)} \qquad \text{(B-3)}$$

In a steady state solution, with R is the pyrolysis rate:

$$M' = M + R \qquad \text{(B-4)}$$

Hence, we can deduce the following equation assuming T_e = 1200K,
$*_e$ = 1,3 kg/m^3; T_e = 300K; g = 9,81 ms^{-2} and a = 0,7:

$$\mathbf{M} = \frac{\mathbf{2{,}33 A_W \sqrt{H}}}{\left[\mathbf{1 + 1{,}6\left(1 + \frac{R}{M}\right)^{2/3}}\right]^{3/2}} \qquad \text{(B-5)}$$

If we assume that the combustion is controlled by the ventilation, the air entrance flow M and the pyrolysis R are proportional; M/R = ∀.

For example for cellulosic material it is often assumed that = 5,5.
So with this value the equation B.5 gives:

$$\mathbf{M = 0{,}5 A_W \sqrt{H}} \qquad \text{(B-6)}$$

or

$$\mathbf{R = 0{,}091\, A_w \sqrt{H}} \qquad \text{(B-7)}$$

This last relation is the relation of Kawagoe.

Combination horizontal and vertical opening

Considering a fire compartment with a vent and a window, see Figure B-1, the opening factor can be calculated by the following assumptions:

- the height of the compartment h_c is 4,3 m
- the total surface of the compartment At is 70 m^2
- the height of the window h is 2,0 m
- the width of the window W is 1,5 m
- the surface of the window A is 3 m^2
- the sill height of the window h_s is 1,2 m
- the surface of the vent Ah is 2 m^2.

According to the Figure 6-3,

$h_1 = h/2 + (h_c - h - h_s) = 2{,}1$ m

$$\frac{\mathbf{A_h \sqrt{h_1}}}{\mathbf{A\sqrt{h}}} = \mathbf{0{,}683} \text{ and } A_h/A = 0{,}66 \qquad \text{(B-8)}$$

then $f_k = 2{,}3$

and the global opening factor taking into account the horizontal opening (vent) is the following:

$$\mathbf{O = A_w \sqrt{h_a} / A_t = f_k A_h \sqrt{h} / A_t = 2{,}3 * 3 * \sqrt{2} / 70 = 0{,}139} \qquad \text{(B-9)}$$

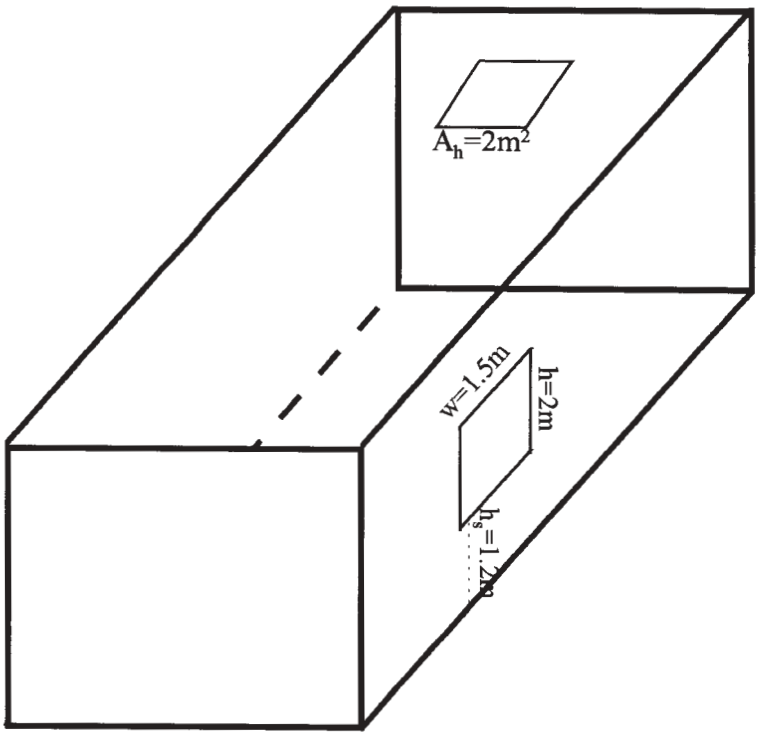


Figure B-1: Dimensions of the compartment.

Heat loss through openings

In furnaces, the quasi-steady state leads to a similar temperature between wall surface and gas, and due to the clean combustion, the gas is optically thin. So the most radiative effect comes from the wall. But due to the small size of the openings, it can be assumed that the radiative losses through openings can be calculated using the black body law.

In the case of a natural fire scenario, the smoke is optically thick, so all the incoming radiation is absorbed. The low temperature of walls under this layer and the large emissivity of walls show that only the radiation from the smoke layer surface in regards to the openings is lost.

A simple comparison between convective and radiative heat loss can be done: considering a homogeneous temperature of 600°C, a window of A_w surface and H height, the equation (B-1) can be used to calculate the inflow and deducing the outflow from a steady state. Then the convective loss through the window is:

$$Q_c = 360\ A_w\ H^{1/2} \quad \text{(kW)} \qquad \text{(B-10)}$$

Considering the maximum radiative power (black body) through the window, the radiative loss is:

$$Q_r = 33{,}0\ A_w \quad \text{(kW)} \qquad \text{(B-11)}$$

So the height of the window has to be about 0,01m to obtain a possible comparison between both heat losses. With a one-meter height, the ratio is about 10.
So for the NFSC research we propose to neglect the radiative heat loss through openings when the temperature is low (less than 800°C).

Nevertheless, when the fire is fully developed and the temperature goes to about 1.000 °C, the radiation through opening becomes close to the convective energy. For example, a fire in a room of 25 m^2 with an opening of 2,6 m^2 gives a distribution of energy shown in the Figure B-2.

This figure indicates the energy loss by radiation through openings may reach 20 % of the energy loss through openings. Moreover, neglecting the radiation loss through opening may overestimate the temperature by 200°C as can be shown with this example in the Figure B-3 (temperature-time curve).

So when the fire is fully developed and the temperature is high (more than 800°C), neglecting the radiation through openings is possible, but a strong over-estimation is resulting.

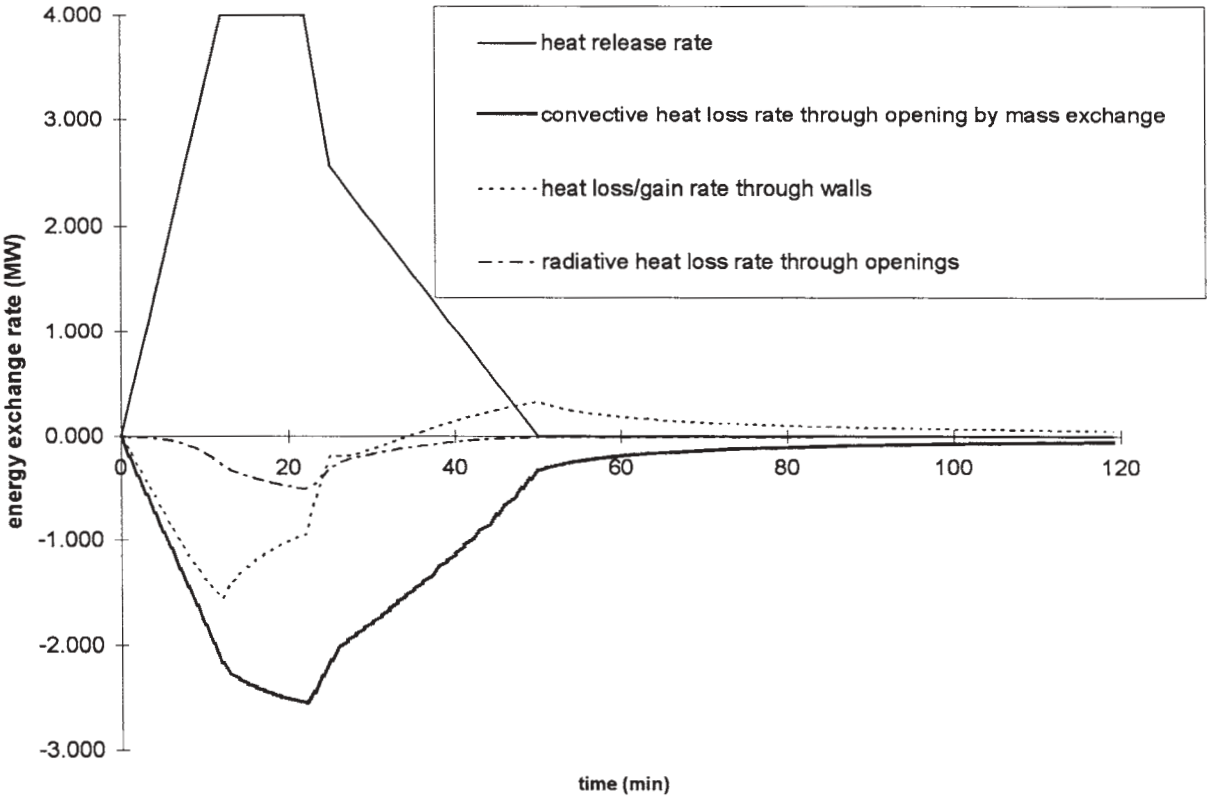


Figure B-2: Distribution of the released energy.

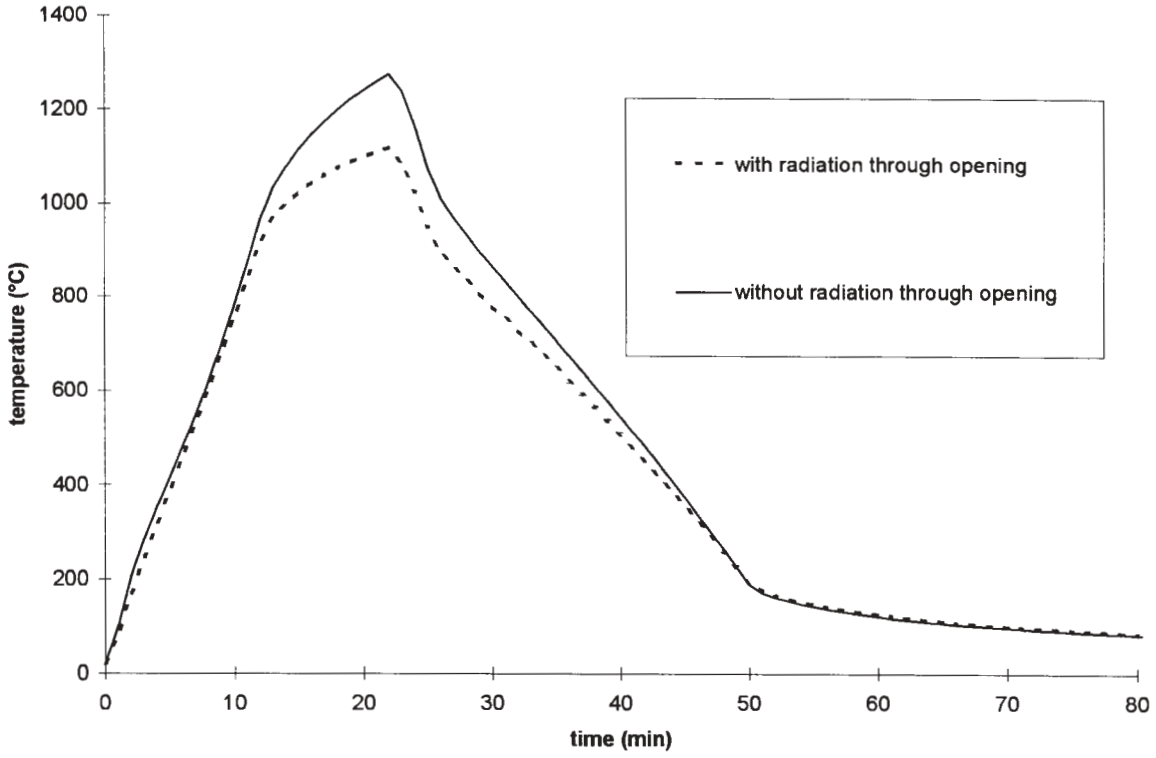


Figure B-3: Calculated temperature with and without radiation through opening.

12 APPENDIX C: PLATE THERMOMETER, BACKGROUNDS/PHYSICS

General

The discussion below is an attempt to theoretically prove the case of the Plate Thermometer as an appropriate instrument for controlling fire resistance furnaces. It will be shown that, under simplifying assumptions, the thermal exposure of a test specimen is almost independent of properties of the furnace if the furnace is controlled such that Plate Thermometers follow a standard curve, whereas the thermal exposure does depend on furnace properties if the furnace is controlled on basis of small thermocouple readings. The treatment follows ref. [8-3].

Model

Figure C-1 depicts the model representing a fire resistance furnace. In the notation, the subscripts refer to the following items: specimen (s), furnace wall (w), furnace gas (g), Plate Thermometer (pt).
The model distinguishes between convective heat transfer to the PT and to a specimen. The convective heat transfer coefficients are denoted as α.

Heat Flux

If the furnace geometry approximates an ideal case of two infinite parallel plates, each having an emissivity equal to 1, the net heat flux entering the specimen is given by

$$Q_s'' = \alpha_s \cdot (T_g - T_s) + \varepsilon_g \cdot \sigma \cdot T_g^4 + (1-\varepsilon_g) \cdot \sigma \cdot T_w^4 - \sigma \cdot T_s^4$$

Simplifying this expression by defining T_r through:

$$T_r^4 = \varepsilon_g \cdot T_g^4 + (1-\varepsilon_g) \cdot T_w^4$$

and allowing for non-unity emissivity of the test specimen, the first equation reduces to

$$Q_s'' = \alpha_s \cdot (T_g - T_s) + \sigma \cdot (T_r^4 - \varepsilon_s \cdot T_s^4)$$

Notes :

1. When non-unity values for the emissivity of furnace walls and specimen are allowed in the model, the net heat flux cannot be expressed in a simple form any longer (except for some ideal textbook cases). This is because heat emitted by the furnace walls is partly reflected by the specimen, then again partly by the furnace walls etc. This leads to a set of equations that can be solved by e.g. the Hottel zone method. The furnace gases absorbing and emitting make this behaviour more complicated.

2. Similarly, the equations are valid for an infinitely large furnace wall opposite an equally infinite specimen. With finite dimensions and non-unity surface emissivities, a more complex expression is needed.

For the net heat flux entering the Plate Thermometer, a similar expression holds:

$$Q''_{pt} = \alpha_{pt} \cdot (T_g - T_{pt}) + \varepsilon_r \cdot \sigma \cdot T_r^4 - \sigma \cdot \varepsilon_{pt} \cdot T_{pt}^4$$

But Q''_{pt} is zero since a PT has a negligible heat capacity. Subtracting the last two equations and rearranging, we find:

$$Q''_s = \alpha_{pt} \cdot (T_{pt} - T_s) - (\alpha_{pt} - \alpha_s) \cdot (T_g - T_s) + \sigma \cdot (\varepsilon_{pt} \cdot T_{pt}^4 - \varepsilon_s \cdot T_s^4)$$

And this reduces to a simple expression under the following assumptions:
1. The convective heat transfer coefficients α_s and α_{pt} are equal (=α). Typical values of convective heat transfer coefficients are: α_s = 10, α_{pt} = 15, α_{tc} = 150 (W/m^{2}K).
2. The surface emissivities ε_s and ε_{pt} are equal (=ε) (and close to 1, see discussion above). Typical values are : ε_{pt} = 0,9 (blackened steel), ε_s= 0,7-0,9 (concrete, ceramic fibre, oxidized metal)

The reduced expression reads:

$$Q''_s = \alpha \cdot (T_{pt} - T_s) + \varepsilon \cdot \sigma \cdot (T_{pt}^4 - T_s^4)$$

Under these assumptions, the heat flux to a specimen depends only on:
1. The properties of the specimen, determining its temperature response;
2. The temperature reading of the Plate Thermometer T_{pt}
3. The convective heat transfer coefficient α

Thus, the dependence of furnace properties is limited to the relatively unimportant convective heat flux. This effectively proves harmonised thermal load. On the other hand, the derivation shows where, how and to what extent harmonisation breaks down when the assumptions made are not all met. It is easy to show that e.g. the furnace gas temperature T_g enters the expression for Q''_s if the effective convective heat transfer coefficients for the specimen and for the PT are different; when the radiative properties of the specimen differ substantially from those of the furnace walls, the "radiation temperature" T_r enters the expression, and thereby T_w and T_g .
Since the work within CEN/TC127/Ad hoc 14 and Ad hoc 7 has shown that T_w and T_g vary with each furnace, a source of deviations is identified.

Example

The above treatment enables –at least in principle- a quantified estimation of the individual effects.
For the convective part, an example illustrates the effects:

Assume the following instantaneous values:
T_g = 900 °C
T_w = 770 °C
T_{pt} = 800 °C
T_s = 500 °C
α_s = 10 W/m^{2}K
α_{pt} = 15 W/m^{2}K

With these values, the nominal convection term is:

$$\alpha_{pt} \cdot (T_{pt} - T_s) \quad = 4{,}5 \text{ kW/m}^2$$

whereas the neglected term is:

$$(\alpha_{pt} - \alpha_s) \cdot (T_g - T_s) \quad = 2{,}0 \text{ kW/m}^2$$

It should be borne in mind however, that the convective contribution to the overall heat flux is small at the high temperatures involved. With
ε_s = 0,9
ε_{pt} = 0,9

The radiative term evaluates to:

$$\varepsilon_{pt} \cdot \sigma \cdot T_{pt}^4 - \sigma \cdot \varepsilon_s \cdot T_s^4 \quad = 49{,}4 \text{ kW/m}^2$$

So that the error made by neglecting the differences between convective heat transfer coefficient or PT and specimen =2,0/(2,5+49,4) or just below 4%.
A similar "error estimate" is not easily made for the radiative terms, since this involves a not-so-simple evaluation of the radiative heat balance in a furnace.

TC Control

If the furnace is not controlled by PT but by TC, a similar argument can be made. However, since the thermocouple receives radiation almost equally from the test specimen and from the furnace environment, the equation for heat flux entering the TC reads:

$$Q_{tc}^{"} = \alpha_{tc} \cdot (T_g - T_{tc}) + 1/2 \cdot \varepsilon_r \cdot \sigma \cdot T_r^4 + 1/2 \cdot \varepsilon_s \cdot \sigma \cdot T_s^4 - \sigma \cdot \varepsilon_{pt} \cdot T_{tc}^4$$

and the equation for the heat flux entering the specimen, again after subtracting the above equation, reads:

$$Q_s'' = \alpha_{tc} \cdot (T_{tc} - T_s) - (\alpha_{tc} - \alpha_s) \cdot (T_g - T_s) + \sigma \cdot (\varepsilon_{tc} \cdot T_{tc}^4 - \varepsilon_s \cdot T_s^4) + 1/2 \cdot \sigma \cdot (\varepsilon_r \cdot T_r^4 - \varepsilon_s \cdot T_s^4)$$

We see that, due to the large difference between α_s and α_{tc}, the convective term involving $(T_g - T_s)$ does not disappear; to the contrary, if α_{tc} may indeed be estimated at 150 W/m^{2}K, the term can be significant. The same goes for the radiative terms : the term involving furnace radiation is far from eliminated.

The above observations show that under TC control and the same simplifying assumptions, the heat flux to the specimen depends on furnace properties (T_g, α_{tc}).

Experimental evidence

The tests carried out within the proving test programme of CEN TC 127 ad hoc 14, Phases 1 and 2, can be seen as corroborating evidence to the theoretical analysis.

In Phase 1, 14 different laboratories conducted one calibration test each, i.e. a test with a concrete wall fitted with five "calibration elements" for test specimen. The tests were conducted under TC control. The results showed a considerable scatter in the exposed side temperatures of the calibration elements.

When the test results were processed to predict the outcome of each test, had the test been conducted under PT control, the predicted response showed a markedly smaller scatter. This was later confirmed in a series of three tests, equal in all aspects except furnace control now on basis of PT.

Conclusions

This Annex gives the theoretical background of the PT versus TC discussion. Satisfactory explanations are given why PT control should work, and why TC control would fail.

The theoretical analysis also offers a basis for further work, e.g. for assessing the influence of transparent specimens or of highly heat absorbing test specimens.

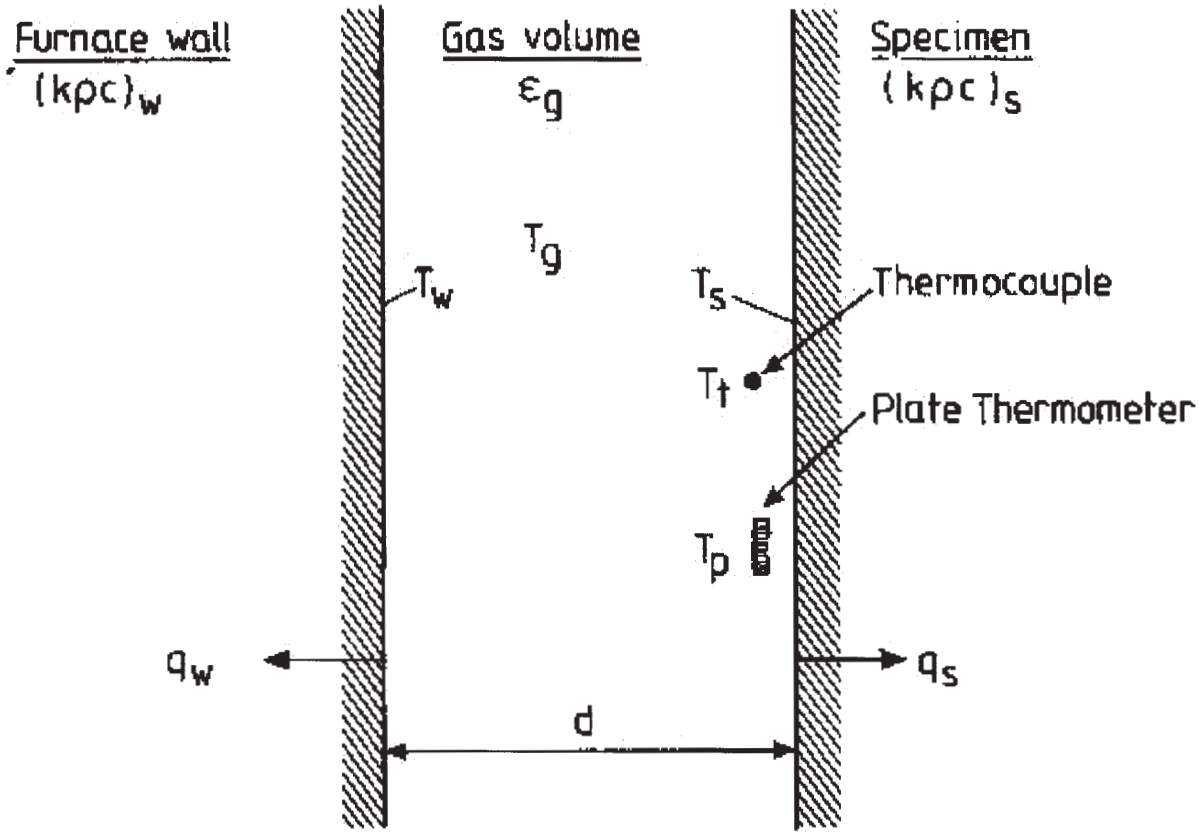


Figure C-1: Simplified one-dimensional model of fire test furnace.

13 APPENDIX D: BREAKING OF GLASS (THEORETICAL ANALYSIS)

Assumptions

1. Windowpane supported by well insulating frame, e.g. timber (cf. Figure D-1.)
2. Fast temperature increase, such as to be expected under flash over conditions.
3. Hooke's law hold, i.e.: $\sigma = E.\ \varepsilon$
   with: σ is strain [N/mm^2]
   E is modulus of elasticity [N/mm^2]
   ε is strain [-]
4. Thermal elongation of glass is given by: $\varepsilon_{thermal} = \alpha.\Delta T$
   with: $\varepsilon_{thermal}$ is thermal induced strain [-]
   α is specific elongation [m/m°C]
   ΔT is temperature increase [°C]
5. The following mechanical properties for glass hold (for temperature range of interest):
   modulus of elasticity of glass: $E_{glass} =$ 0,5 x 10^{+5} N/mm^2
   tensile strength of glass: $\sigma_{tens.} =$ 40 N/mm^2
   thermal elongation of glass: $\alpha_{glass} =$ 8 , 10^{-6}

Breaking of the glass occurs if the tensile stress of the glass is reached.

Breaking mechanisms

Breaking of the glass due to (possibly) two effects:

(1) the elongation due to the non uniform temperature distribution along the window pane is restrained (internal restraint by the window pane itself, cf. Figure D-1).

(2) the curvature due to the non uniform thermal distribution across the window pane is restrained (due to external restraint by the frame, cf. Figure D-2).

Numerical evaluation

Breaking of the glass due to restrained elongation occurs at a temperature difference along the glass pane of: (see also Figure D-1)

$\Delta T_{(1)} = \sigma_{tens} / \alpha_{glass} . E_{glass} =$ 40/ 8 . 10^{-6} · 0,5 x 10^{+5} = 100 °C.

This assumes that the area under tensile is negligible compared to the area under compression; in practical situations this condition will easily be met.

Breaking of the glass due to restrained curvature occurs at a temperature difference across the glass of: (see also Figure D-2)

$$\Delta T_{(2)} = 2 \cdot \sigma_{tens} / \alpha_{glass} . E_{glass} = 2 \cdot 40 / 8 . 10^{-6} \cdot 0{,}5 \times 10^{+5} = 200 \text{ °C}.$$

This assumes complete restraint of the thermal curvature; in practical situations, this will not occur; hence the value of $\Delta T_{(2)}$ may be significantly higher.

Conclusions

The critical value of $\Delta T_{(1)}$ will be reached earlier than that of $\Delta T_{(2)}$. Hence, breaking of the glass due to restrained elongation (ref. B-(1)) is the relevant cracking mechanism. Assuming a well insulating frame (e.g. timber), the parts of the glass protected by the frame, initially will hardly undergo a temperature increase. Hence, the critical condition for cracking of the glass will be reached for a temperature increase at the direct exposed glass of approx. 100 °C. Under standard fire test conditions, this will happen only a few minutes after commencing the test (depending on the glass and the furnace). This is confirmed by test evidence.

If under natural fire conditions flashover occurs, at the moment of flashover a rapid temperature rise will take place, which is similar to that in the early phase of the standard fire curve. Hence, it seems reasonable to assume that flashover will lead to cracking of (all) the glass panes. If no flashover occurs - and consequently no rapid temperature rise is to be expected - the temperature gradients in the glass are less pronounced and (general) breaking will not occur. However, under these conditions, cracking of the glass is possible e.g. due to local effects of the primary fire (depending on location and severity). In fact, this may very well initiate flashover.

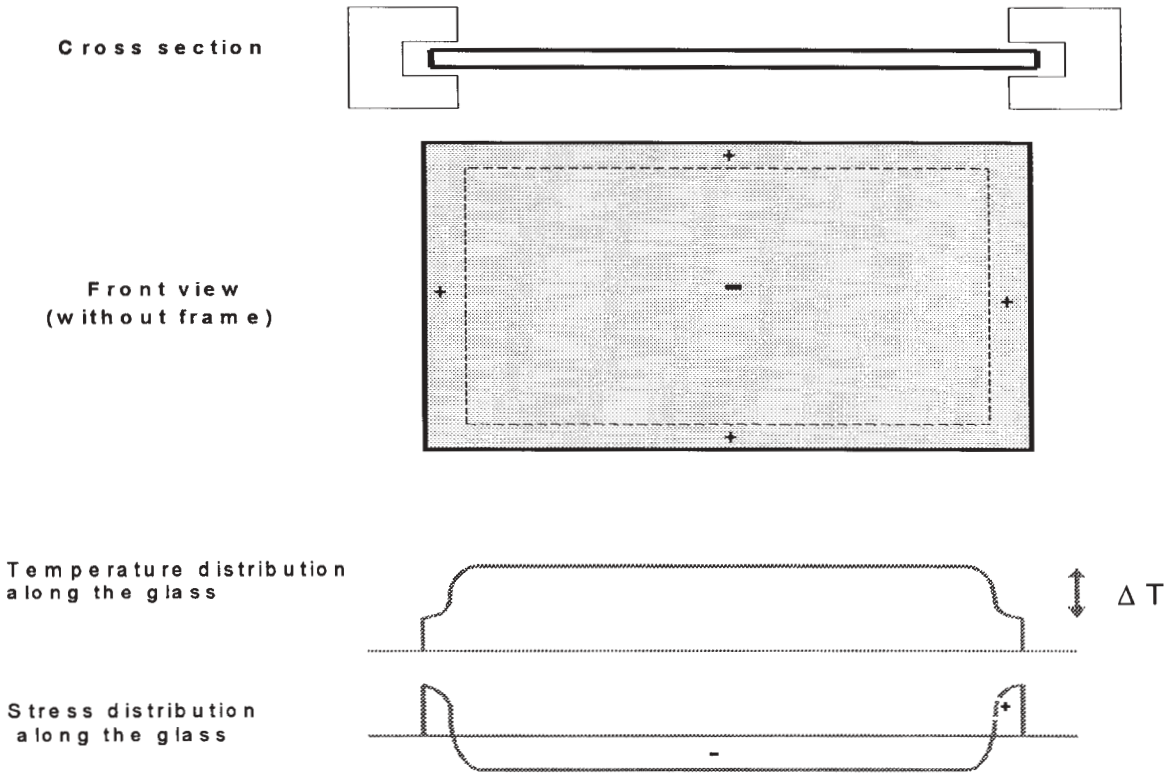


Figure D-1: Effect of non-uniform temperature distribution along the glass.

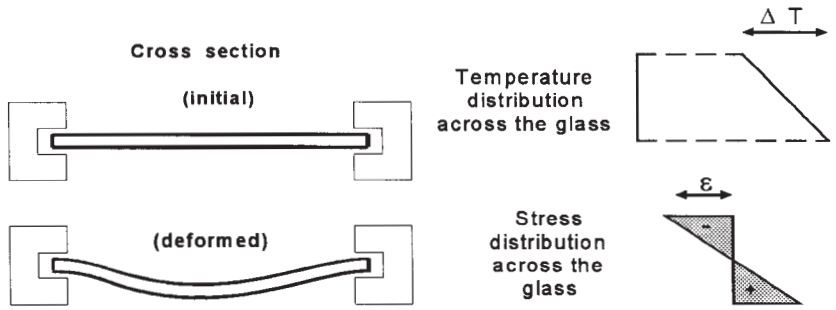


Figure D-2: Effect of non-uniform temperature distribution across the glass.

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IV. WORKING GROUP 4

STATISTICS

1 INTRODUCTION

Fire safety in buildings is a major concern of building regulations. At present in most countries detailed prescriptive regulations are given to the designer to be followed when designing a building. However, a strong move towards fire safety engineering and performance based regulations can be observed during the last years world wide.
The following statistical research aims at providing data on different aspects of fire safety to help engineers in their planing of fire safe buildings and the evaluation of their fire safety concept. The data was established within the frame work of the European research program "Natural Fire Safety Concept" sponsored by the ECSC. The members of the research program are given in Table 1.1. Working group 4 under the leadership of Prof. M. Fontana was responsible for the statistical part of that program. The WG4 partners are written in bold.

Company	Name	Address
BCSA **Roger Pope Associates (working for BCSA)**	**P.J. Williams** **Dr. R.J. Pope**	**4, Whitehall Court GB-London SW1A 2ES** **870 Mannamed Road GB-Plymouth PL3 4SY**
CREA Structural Engineering	S. Pustorino	Porte San Domenico B/G I-56125 Pisa
CTICM	**D. Joyeux** **J. Kruppa**	**Domaine St. Paul, P.O. 64 F-78470 St. Rémy**
ETH Zürich (working for ECCS)	**Prof. M. Fontana** **C. Fetz**	**ETH-Hönggerberg CH-8093 Zürich**
Halfkann + Kirchner (working for SAES)	**U. Kirchner**	**Richard-Lucas-Str. 4 D-41812 Erkelenz**
LABEIN	G. Aurtenetxe	Cuesta de Olabeaga, 16, E-48013 Bilbao
Profil ARBED (leader of research)	**J.B. Schleich** **L.G. Cajot**	**66, rue de Luxembourg L-4009 Esch/Alzette**
Studiengesellschaft Stahlanwendung (SAES)	**Heise**	**Breite Strasse 69 D-40213 Düsseldorf**
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Universität Bochum	**Prof. Kindmann** **H. Schweppe**	**Universitätsstr. 150 D-44780 Bochum**
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V.T.T: Building Technology	**M. Kokkala**	**Kivimiehentie 4 P.O Box 1803 FIN-02044 Espoo**

Table 1.1: Members of the NFSC-research program

This statistical report contains data from 40.000 fires in the Canton of Berne collected by WG4 and international data from different sources on various aspects of fire safety namely sprinkler performance.

2 BERNE DATABASE ON REAL FIRES

For the NFSC research WG4 has collected a large new database of real fires in the canton of Berne for the period 1986 to 1995. The major losses (> 10^6 CHF) have been studied in detail (see chapter 2.1) and all 40.000 losses were studied on the basis of selected data from the electronic database of GVB (Gebäude-Versicherung des Kanton Bern) (see chapter 2.2).

2.1 MAJOR FIRE LOSS SURVEY CANTON OF BERNE 1986 - 1995

All fires in buildings causing damage to the building larger than 1 Mio CHF (~ 700.000 ECU) where collected and analysed with the Swiss Risk Evaluation Method SIA Doc 81 [1] (see Table 2.1).

Analysis of the major fires of the canton Bern / loss > 1.0 Mio. CHF

								casualities		building informations				CHF	CHF	%	CHF	CHF	CHF	cause of loss				deficiency				modi-fied	fire risk evaluation according to SIA-Dok.81								
damage-number	occupancy	no. of floors	city	cause	fire origin	time of day	day	fatalities N °	injuries N °	type	mat-erial	age	concept	insured building value	building damage	damage / value	damage contents	damage total	transf. loss neigh-bour building	% fire	% smoke	% water	passive prot.	electr	fire brig.	fire water		γ	P	N	S	F	A	B	R	R-Gr.
4288024	29	6	Moutier	22	rest	6	3	0	0	Z	3	1972	1	3.60	1.00	0.28			0.00	30	50	20			1.4			4.93	0.52	1.00	1.40	1.43	1.00	0.26	0.26	1.30
8164001	68	1	Utzenstorf	49	heater	7	1	0	0	G	3	1955	2	30.0	1.06	0.04			0.00	80	10	10			5		g =1	3.50	1.25	1.00	2.55	1.32	1.00	0.37	0.37	1.30
2377029	20	3	Saanen	24	heater	14	5	0	0	G	4	1978	1	5.16	1.00	0.19			0.00	30	40	30						2.78	0.83	1.00	1.35	1.32	1.00	0.46	0.46	1.30
7253002	72	1	Liesberg	52	hall	17	7	0	0	G	4	1961	2	5.00	1.20	0.24			0.00	80	10	10				U		2.35	1.38	1.00	2.07	1.20	1.00	0.55	0.55	1.30
9053002	19	1	Büren	98	bridge	4	3	0	0	G	2	1821	1	1.84	1.47	0.80			0.00	90		10						1.44	1.21	1.00	1.35	1.00	1.00	0.90	0.90	1.30
6288914	51	4	Moutier	25	store	15	4	0	0	G	3	1968	1	5.06	1.43	0.28			0.00	20	70	10						1.20	2.07	1.00	1.40	1.36	1.00	1.08	1.09	1.30
8077004	34	4	Koppigen	51	citchen	12	3	0	0	G	5	1948	1	6.05	3.21	0.53			0.00	80	10	10	2.8	2	3.4		g =1	1.12	2.89	1.00	2.07	1.20	1.00	1.16	1.16	1.30
6204014	80	8	Interlaken	19	room	19	6	0	0	Z	4	1906	1	8.00	4.30	0.54			0.00	40	20	40	4				g =1	1.12	1.61	1.00	1.40	1.32	1.00	0.87	0.87	1.30
2038073	29	4	Bern	91	stone floor	10	5	0	0	G	5	1900	1	5.20	1.89	0.36	0.56	2.45	0.00	40	20	40	3				g =1	0.99	2.77	1.00	1.60	1.32	1.00	1.31	1.31	1.30
0101024	16	3	St.-Imier	51	platform	12	5	0	0	V	3	1952	1	3.27	1.50	0.46			0.00	50	40	10	2.7					0.98	2.20	1.00	1.40	1.43	1.20	1.10	1.32	1.30
1078002	14	5	Kruschthal	72	cell	16	2	1i	0	Z	3	1895	1.2	6.45	1.62	0.25			0.00	50	40	10				U		0.97	2.31	1.00	1.45	1.82	1.00	0.87	0.87	1.30
5439001	29	5	Hilterfingen	53	citchen	22	7	0	0	Z	5	1900		3.40	2.10	0.62			0.00	40	20	30	1.2				g = 1	0.91	2.50	1.00	1.35	1.32	1.00	1.40	1.41	1.30
4301003	20	5	Tavannes	52	flat	4	3	1i	0	Z	3	1929	1	1.60	1.29	0.81			0.00	20	60	20	2				g =1	0.91	2.54	1.00	1.35	1.32	1.00	1.42	1.43	1.30
3057002	28	3	Lengnau	51	transf	5	5	0	2f	V	5	1900	1	1.72	1.20	0.70			XX	90		10	2					0.87	2.57	1.00	1.30	1.32	1.00	1.50	1.50	1.30
7187003	80	6	Adelboden	81	room	20	4	0	1f	V	5	1910	1	2.80	2.58	0.92			0.00	90		10	6.8					0.86	1.25	0.72	1.15	1.00	1.00	1.51	1.51	1.30
4452058	73	2	Thun	82	workshop	14	4	0	1i	G	1	1984	1	2.50	1.45	0.58			0.00	60	30	10						0.86	1.77	1.00	1.40	1.00	1.20	1.26	1.52	1.30
1428003	81	2	Lenk	91	barn	8	2	0	1i/1f	V	2	1850	1	1.08	1.09	1.01			0.00	90	10		2.6		5	U	g =1	0.84	1.05	0.50	1.35	1.00	1.00	1.55	1.55	1.30
7013002	63	4	Aarwangen	51	warehouse	22	6	0	0	G	5	1912	1	2.30	1.08	0.47	0.6	1.7	0.00	60	10	30	2.6					0.82	1.48	0.72	1.30	1.00	1.00	1.58	1.58	1.30
4189042	25	4	Frutigen	22	flat	16	1	0	0	V	5	1830	1	2.00	1.74	0.87			0.00	40	10	40	1.2					0.81	1.66	0.80	1.30	1.00	1.00	1.60	1.60	1.30
1021034	66	1	Langenthal	41	heater	17	1	0	1i	G	2	1946	1	1.45	1.19	0.82	2	3.2	0.00	70	10	20	2.4		5			0.78	2.34	1.00	1.40	1.00	1.00	1.67	1.67	1.30
3034008	63	3	Thunstetten	24	silo	14	2	0	0	V	1	1973	1	2.46	1.38	0.56			0.00	70	30		4					0.78	1.92	1.00	1.35	1.00	1.25	1.42	1.71	1.30
1420006	66	1	Erlenbach	24	hall	12	4	0	2f	G	2	1944	1	1.43	1.26	0.88			0.10	70	10	20	6.7		1			0.75	1.87	0.80	1.35	1.00	1.00	1.73	1.73	1.30
2006001	61	9	Lyss	24	silo	9	3	0	0	V	3	1959	1	3.33	1.85	0.56			0.00	60	30	10	2				g =1	0.74	3.52	1.00	1.40	1.43	1.00	1.75	1.76	1.30
4438001	73	5	Heimberg	73	warehouse	14	4	0	0	V	4	1979	2	1.63	1.34	0.82			0.00	60	30	10					g =1	0.67	4.03	1.00	2.07	1.00	1.00	1.94	1.95	1.30
3321001	66	1	Orpund	51	workshop	3	4	0	0	G	2	1948	1	3.25	1.59	0.49			0.00	80		20	2.4	2				0.67	2.10	1.00	1.30	1.00	1.20	1.61	1.94	1.30
3411001	51	2	Lauperswil	51	toilette	19	5	0	0	G	2	1975	2	1.20	1.25	1.04	3.8	5	0.00	80		20	2.4	2	1		g =1	0.66	3.60	1.00	1.83	1.00	1.00	1.96	1.96	1.30
9470001	39	4	Bettenhausen	22	room	11	4	0	2f	V	2	1836	1	3.20	1.08	0.34			0.00	30	60	10	1.2				g =1	0.61	2.57	1.00	1.00	1.20	1.00	2.14	2.15	1.30
6260003	31	3	Ferenbalm	81	stone floor	3	4	0	3f	V	2	1902	1	1.50	1.26	0.84			0.00	70	10	20	2	2			g =1	0.59	2.02	1.00	0.92	1.00	1.00	2.20	2.20	1.30
0042010	31	3	Köniz	51	treshing floor	1	2	0	1f	V	2	1829	1	1.09	1.12	1.03	0.3	1.4	0.00	90		10	2	2			g =1	0.58	3.12	1.00	1.40	1.00	1.00	2.22	2.23	1.30
9038139	63	2	Bern	91	treshing floor	3	7	0	0	V	2	1850	1	8.70	1.76	0.20			0.00	70	10	20	2.4				g =1	0.57	3.65	1.00	1.60	1.00	1.00	2.28	2.28	1.30
2038038	26	4	Bern	22	room	7	2	1i	0	V	4	1800	1	2.64	2.40	0.91			0.00	40	20	40	2-7				g =1	0.51	3.58	1.00	1.60	1.32	1.20	1.68	2.03	1.30
9310004	76	1	Brügg	49	shelter	20	5	0	0	G	3	1968	2	14.0	1.77	0.13			0.00	20	70	10	3.4					0.55	4.71	1.00	1.40	1.43	1.00	2.35	2.35	1.30
1413005	31	3	Rüderswil	72	treshing floor	13	6	0	0	V	2	1876	1	1.45	1.51	1.04			0.00	70	10	10	2		5		g =1	0.50	2.96	1.00	1.15	1.00	1.00	2.57	2.58	1.30
5042018	31	2	Köniz	81	treshing floor	15	2	0	0	V	2	1837	1	1.42	1.24	0.87	0.25	1.49	0.00	90		10	2				g =1	0.50	3.65	1.00	1.40	1.00	1.00	2.60	2.61	1.30
9397002	31	3	Mühlethurnen	51	treshing floor	19	4	0	0	V	2	1928	1	1.06	1.10	1.04			0.00	100			7		4.5		g =1	0.48	3.12	1.00	1.15	1.00	1.00	2.71	2.71	1.30
3046002	31	3	Vechigen	24	room	17	2	0	0	V	2	1750	1	1.00	1.01	1.01	0.1	1.1	0.00	80		20	2		1		g =1	0.46	3.85	1.00	1.35	1.00	1.00	2.85	2.85	1.30
4452124	25	4	Thun	53	citchen	17	2	0	1i	V	2	1873	1	0.98	1.05	1.07			0.00	50	40	10	1.2				g =1	0.44	4.51	1.00	1.40	1.10	1.00	2.93	2.93	1.30
2082009	38	3	Oberburg	51	treshing floor	14	5	0	0	V	5	1932	1	1.20	1.08	0.90			0.00	70	10	20	2			U	g =1	0.44	3.97	1.00	1.35	1.00	1.00	2.94	2.95	1.30
2099002	31	2	Renan	51	treshing floor	7	2	0	1f	V	2	1580	1	1.01	1.05	1.04			0.00	60	10	30		2			g =1	0.43	3.45	1.00	1.15	1.00	1.00	1.96	3.00	1.30
4050002	31	2	Evilard	61	roof	15	7	0	0	V	5	1845	1	1.15	1.07	0.93			0.00	90		10	2	1		U	g =1	0.43	3.51	1.00	1.15	1.00	1.00	3.02	3.03	1.30
6076005	31	3	Kirchberg	21	treshing floor	13	7	0	0	V	2	1900	1	1.13	1.23	1.09	0.2	1.4	0.00	70	10	20	2				g = 1	0.43	3.85	0.95	1.35	1.00	1.00	3.00	3.00	1.30
1021019	73	4	Langenthal	24	roof	14	1	0	1i	V	2	1915	1	45.0	2.40	0.05			0.00	50	40	10	2.7					0.42	5.48	1.00	1.60	1.32	1.20	2.59	3.12	1.30
3462003	63	5	Lützelflüh	51	warehouse	19	3	0	0	V	4	1910	1	5.04	3.06	0.61				80		20	2.4	2				0.42	4.57	1.00	1.35	1.32	1.20	2.56	3.08	1.30
2006014	31	3	Lyss	73	treshing floor	12	1	0	0	V	2	1936	1	1.14	1.12	0.98			0.00	80	10	10	2.6				g =1	0.41	4.44	1.00	1.40	1.00	1.00	3.17	3.18	1.30
5259001	31	2	Kriechenwil	51	treshing floor	11	7	0	0	V	2	1840	1	1.10	1.16	1.05			0.00	80	10	10	2.6		5	U	g =1	0.41	3.65	1.00	1.15	1.00	1.00	3.17	3.17	1.30
1204019	50	4	Interlaken	73	store	3	4	0	2f	V	2	1700	1	1.35	1.07	0.79			1.40	80	10	10	2		5		g =1	0.41	4.49	1.00	1.40	1.00	1.00	3.20	3.21	1.30
1204020	25	4	Interlaken	73	house	3	4	0	0	V	2	1800	1	1.60	1.40	0.87			0.00	70	10	20	2		5		g =1	0.41	4.49	1.00	1.40	1.00	1.00	3.20	3.21	1.30

Table 2.1: Survey of major losses in the Canton of Berne resulting in a loss of the building (not including contents and business interruption) of more than 1 Mio CHF.

1416003	21	3	Trub	61	roof	9	7	0	0	V	2	1761	1	2.01	1.97	0.98	0.3
2304005	31	3	Lamboing	51	treshing floor	2	5	0	0	V	5	1863	1	1.13	1.18	1.04	
9235003	31	3	N'wichtrach	73	platform	23	1	0	0	V	2	1846	1	1.07	1.07	1.00	0.5
2315001	31	3	Jens	52	treshing floor	13	5	0	0	V	2	1869	1	1.00	1.08	1.08	
1034006	31	3	Thunstetten	51	treshing floor	7	2	0	0	V	2	1820	1	1.03	1.05	1.02	0.1
9053010	31	3	B0ren	91	treshing floor	23	5	0	0	V	2	1900	1	0.98	1.01	1.03	
2403007	31	2	R0ti b. Riggisb	23	room	15	7	0	0	V	2	1860	1	1.40	1.40	1.00	
4230014	31	2	Landiswil	81	treshing floor	24	6	0	0	V	2	1855	1	1.38	1.42	1.03	0.65
5057002	31	3	Lengnau	51	treshing floor	1	7	0	0	V	2	1900	1	1.15	1.13	0.98	
2036001	31	3	Ursenbach	81	treshing floor	3	5	0	0	V	2	1850	1	1.62	1.65	1.02	
2261002	31	2	Frauenkappel	51	treshing floor	17	6	0	0	V	2	1866	1	1.26	1.33	1.06	0.85
4038225	73	1	Bern	21	warehouse	5	1	0	0	G	1	1968	1	17.2	1.50	0.09	
2294001	31	2	Saicourt	52	treshing floor	11	5	0	0	V	2	1900	1	1.23	1.25	1.02	
4485004	31	2	Seeberg	53	room	2	7	0	2i	V	2	1809	1	1.39	1.46	1.05	
9027001	31	3	Oeschenbach	51	treshing floor	17	6	0	0	V	2	1800	1	1.01	1.00	0.99	
9314001	31	3	Hermrigen	51	treshing floor	16	2	0	1f	V	2	1874	1	1.12	1.03	0.92	
3153003	31	3	Iffwil	51	treshing floor	19	4	0	0	V	2	1944	1	1.15	1.25	1.09	
1315002	31	3	Jens	91	roof	16	6	0	0	V	2	1880	1	1.03	1.03	1.00	
9292001	31	3	Roches	16	chimney	15	2*	0	0	V	2	1880	1	1.06	1.12	1.06	0.4
7260001	31	2	Ferenbalm	51	stable	8	7	0	0	V	2	1898	1	1.07	1.02	0.95	
67 cases								3 killed	23 injured					248.83 sum of insured value	96.95 sum of damage	0.39 Σdamage/ Σvalue	

1416003	2.3	0.00	70		30		1	5		g =1	0.40	3.74	1.00	1.15	1.00	1.00	3.25	3.26	1.30
2304005		0.00	70	10	20	2	2	5		g =1	0.40	3.56	1.00	1.00	1.10	1.00	3.24	3.24	1.30
9235003	1.6	0.00	100							g =1	0.37	4.68	1.00	1.35	1.00	1.00	3.46	3.47	1.30
2315001		0.00	70	10	20	2	2			g =1	0.37	3.51	1.00	1.00	1.00	1.00	3.51	3.51	1.30
1034006	1.2	0.00	90		10	2	3	5		g =1	0.37	4.68	1.00	1.35	1.00	1.00	3.46	3.47	1.30
9053010		0.00	100			2.6			U	g =1	0.36	4.68	0.95	1.35	1.00	1.00	3.64	3.65	1.30
2403007		0.00	80	10	10					g =1	0.36	3.65	1.00	1.00	1.00	1.00	3.65	3.65	1.30
4230014	2.07	0.08	80	10	10	2.6				g =1	0.36	3.65	1.00	1.00	1.00	1.00	3.65	3.65	1.30
5057002			60	10	30	2	2			g =1	0.35	4.89	1.00	1.30	1.00	1.00	3.76	3.76	1.30
2036001		0.00	80	10	10	6			U	g =1	0.35	4.21	1.00	1.15	1.00	1.00	3.66	3.66	1.30
2261002	2.18	0.00	80	10	10	2.6	2.4			g = 1	0.36	4.23	1.00	1.15	1.00	1.00	3.68	3.69	1.30
4038225		0.00	85	10	5	2.4					0.35	5.24	1.00	1.60	1.00	1.20	3.12	3.74	1.30
2294001		0.00	80	10	10	2.6	2	5	U	g = 1	0.34	3.85	1.00	1.00	1.00	1.00	3.85	3.85	1.30
4485004		0.00	90		10					g =1	0.34	3.85	1.00	1.00	1.00	1.00	3.85	3.85	1.30
9027001		0.00	80	10	10	2.6				g =1	0.32	4.05	1.00	1.00	1.00	1.00	4.05	4.05	1.30
9314001		0.00	90		10		2			g =1	0.32	4.05	1.00	1.00	1.00	1.00	4.05	4.06	1.30
3153003		0.00	60		40	2.6		1		g =1	0.29	4.44	1.00	1.00	1.00	1.00	4.44	4.45	1.30
1315002		0.00	100			2.6				g =1	0.28	4.68	1.00	1.00	1.00	1.00	4.68	4.68	1.30
9292001	1.5	0.00	100			6.7		1.2		g = 1	0.28	4.68	1.00	1.00	1.00	1.00	4.68	4.68	1.30
7260001		0.00	60		40	2.6	2		U	g = 1	0.23	2.96	0.45	1.15	1.00	1.00	5.72	5.73	1.30

LEGEND

damage number	
1. figure	year
2.-4. figure	city code
5.-7. figure	internal loss number

occupancy	
10-19	Public
20-29	Dwellings
30-39	Farms
40-49	Transport
50-59	Shops
60-79	Industrial
80-89	Hotel
90-99	Annex

cause	
10-29	Firing system and fires as directed
30-39	self lightened
40-49	explosions
50-59	electricity
60-69	lightning strike
70-79	arson and bomb attack
80-89	other known reasons
91	unknown reasons
98/99	terror and commotion

casualities	
i	occupant
f	fire brigade member

typ	
Z	small comparments
G	large comparments
V	no comparmentation between floors

material	
1	steel
2	timber
3	massiv
4	mixed
5	mixed combust.

concept	
1	structural
2	detection
3	sprinkler
4	mixed

fire protection deficiency	
1	insufficient fire resistance of structure
2	insufficient compartmentation
3	insufficient sealing of ducts
4	no active measures
5	escape route insufficient
6	missing fire extinguishers
7	organisational deficiencies
8	insufficient maintenance

electrical deficiency	
1	missing lightning protection
2	missing residual current-switch
3	supply by roof wiring
4	defective installations

Fire brigade deficiency	
1	insufficient alarm organisation
2	insufficient means of transport
3	missing breathing apparatus
4	insufficient training
5	support unit not requested

risk evaluation	
P	potential danger
N	normal measures
S	special measures
F	struct. measures
A	fire occurance
B	potential loss
R	effective risk
R-Gr.	accepted risk

ANALYSIS

	cases	sum of insured value	sum of damage	damage/ Σvalue
total	= 67	248.83	96.95	0.39
combustible (2,5)	= 50	131.9	67.8	0.51
non combustible (1,3,4)	= 17	116.9	29.2	0.25
Public (10-19)	= 3	11.6	4.6	0.40
Dwellings (20-29)	= 11	29.9	16.0	0.54
Farms (30-39)	= 32	44.6	39.7	0.89
Transport (40-49)	= 0	0.0	0.0	0.00
Shops (50-59)	= 3	7.6	3.8	0.49
Industrial (60-79)	= 15	143.3	24.9	0.17
Hotel (80-89)	= 3	11.9	8.0	0.67
Annex (90-99)	= 0	0.0	0.0	0.00

Table 2.1 continued: **Survey of major losses in the Canton of Berne resulting in a loss of the building (not including contents and business interruption) of more than 1 Mio CHF.**

The data shows a correlation between the fire safety factor γ and the relative loss (loss/value at risk), as given in Figure 2.1.

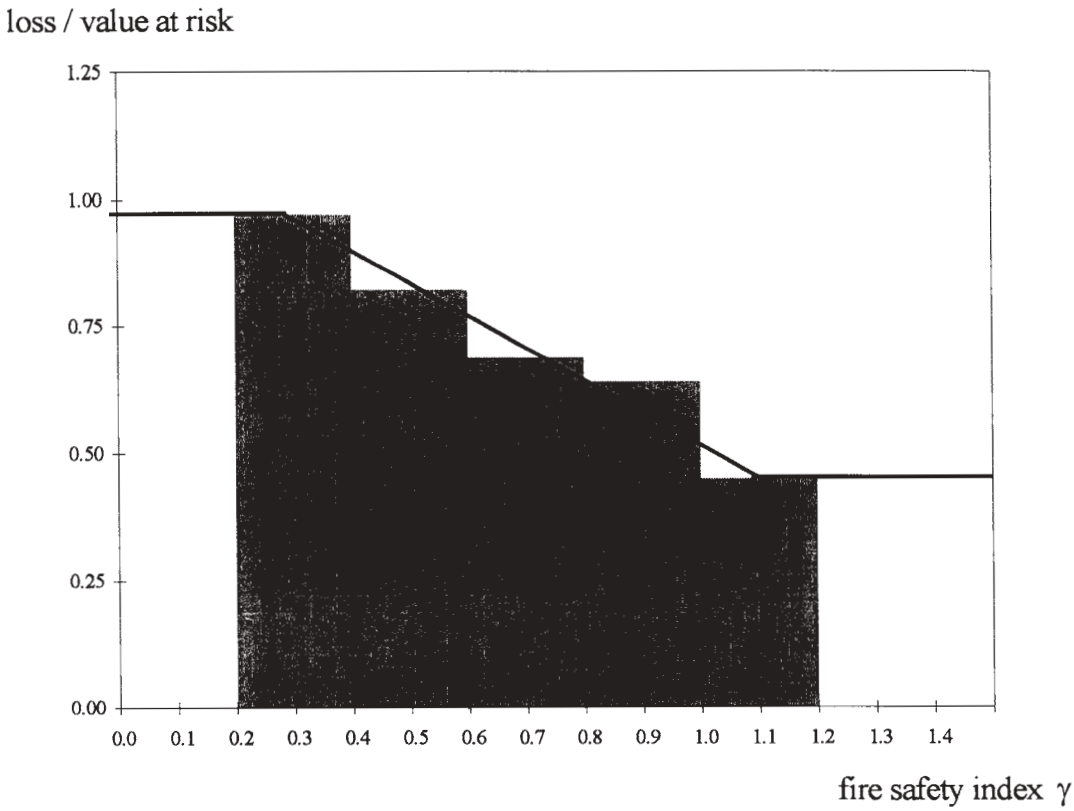


Figure 2.1: Relative loss (loss on building / value of building) compared to the fire safety factor γ according to the Swiss risk evaluation method SIA Doc 81

The loss to be expected in a building decreases with increasing value at risk [13]. The relative loss (loss/ value at risk) as a function of the value at risk is given in Figures 2.2 and 2.3 for different occupancies for the 67 fires in Table 2.1.

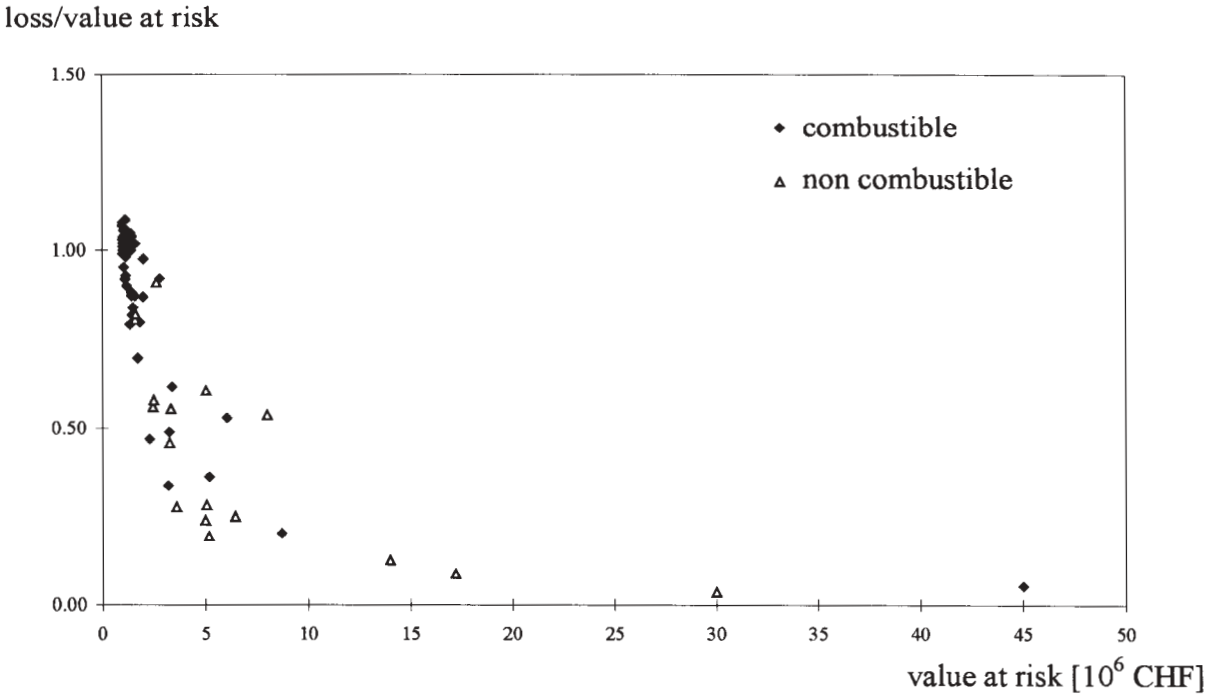


Figure 2.2: Relative loss (loss on building / value of building) compared to the value at risk for different building types (1986-95 all losses > 10^6 CHF)

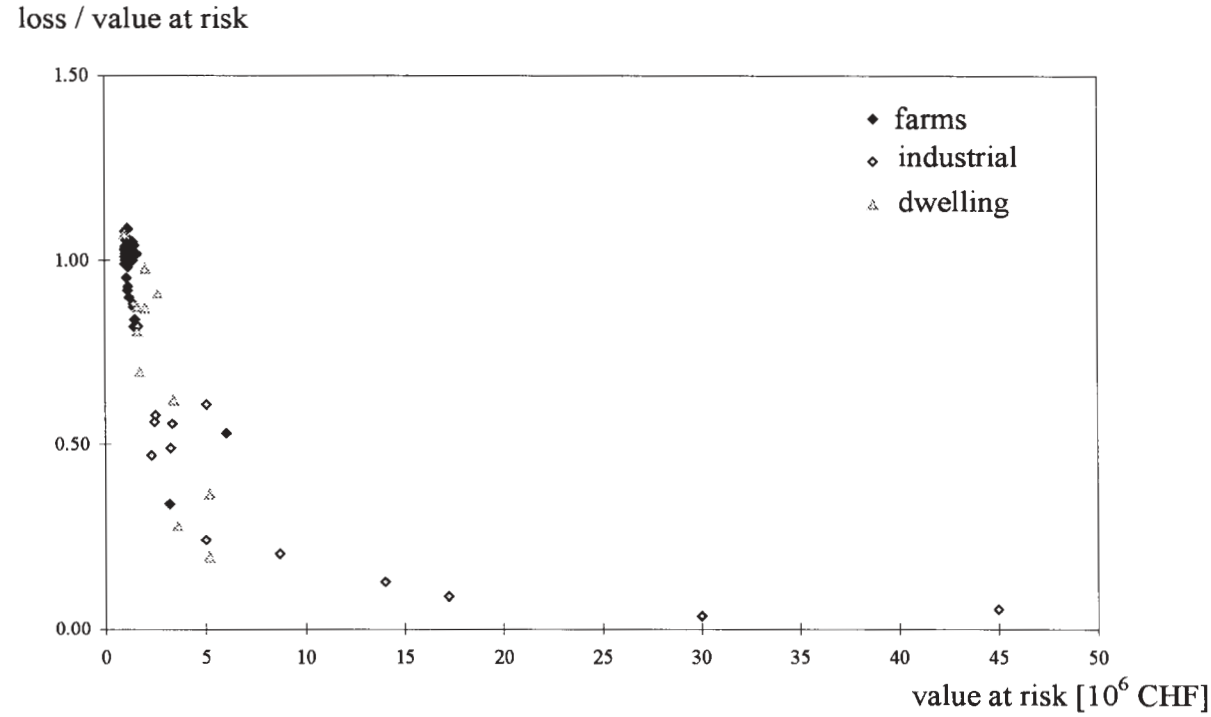


Figure 2.3: Relative loss (loss on building / value of building) compared to the value at risk for different occupancies (1986-95 all losses > 10^6 CHF)

2.2 FIRE LOSS SURVEY (ALL FIRES) CANTON OF BERNE 1986 - 1995

2.2.1 GENERAL

The survey covers all fires (39.104 fires) in the Canton of Berne reported to the Public Building Insurance GVB in the period 1986 to 1995. (Note: Due to the monopolistic insurance system for buildings in Switzerland all buildings must be insured by the Public Building Insurance. Therefore a complete set of data exists.)

2.2.2 PARAMETERS IN DATABASE

For each fire a detailed report is established. The following selected parameters are available on computer files and can be used for statistical analysis:

- Type of fire
- Date of loss
- Place (city)
- Cause of fire
- Type of occupancy
- Fatalities
- Injuries
- Type of building (massive, non-massive [timber])
- Value at risk
- Sum of loss (building only, not contents)

2.2.3 DATABASE

The general data for Berne in 1995 is as follows:

	1995	Average 1986 - 1995
Number of buildings	335.000 Buildings	
Value of the buildings	209.000 million CHF[1]	
Loss due to fire	44 million CHF	46,1 million CHF
Number of claims due to fire	3.800	3.910

Table 2.2: Total number and value of all buildings insured by the GVB and fire losses for the Canton of Berne

[1] 1 US$ ≈ 1.5 CHF (Sept. 1997)

2.2.4 ANALYSIS OF DATA

2.2.4.1 Classes of fire damage

The fires were grouped in the following classes:

Class			
n_0	all		
n_1	0	- 499	CHF
n_2	500	- 999	CHF
n_3	1.000	- 1.999	CHF
n_4	2.000	- 4.999	CHF
n_5	5.000	- 9.999	CHF
n_6	10.000	-19.999	CHF
n_7	20.000	-49.999	CHF
n_8	50.000	-99.999	CHF
n_9	100.000	- 999.999	CHF
n_{10}	> 1.000.000		CHF

An analysis of the data is given in the following tables.

2.2.4.2 Number of fires

Fire damage to building [CHF]	Number of fires	%	Σ %	Interpretation of fire growth (dwellings)
all	39.104	100	100	
0 - 499	12.108	31,0	31,0	
500 - 999	8.354	21,3	52,3	charring only (non-flaming fire)
1.000 -1.999	7.545	19,3	71,6	Self-terminated or extinguished by occupants
2.000 -4.999	6.031	15,4	87,0	
5.000 -9.999	2.243	5,7	92,7	
10.000 -19.999	1.165	3,0	95,7	
20.000 -49.999	537	1,4	97,1	did not spread beyond room of origin
50.000 -99.999	346	0,9	98,0	spread beyond room of origin but controlled by fire brigade
100.000 - 999.999	708	1,8	99,8	
> 1.000.000	67	0,2	100	very large spread (total failure in most cases)

Table 2.3: Number of fires reported over ten years (1986-1995) in the canton of Berne (all occupancies)

	Dwellings			Industrial			Office / Public		
Fire loss class [CHF]	Number of fires	%	Σ %	Number of fires	%	Σ %	Number of fires	%	Σ %
all	24.962	100	100	1.538	100	100	1389	100	100
0 - 499	7.204	28,85	28,8	188	12,2	12,2	283	20,4	20,4
500 - 999	5.592	22,4	51,2	223	14,5	26,7	241	17,4	37,8
1.000 -1.999	5.260	21,1	72,3	265	17,2	43,9	295	21,2	59,0
2.000 -4.999	4.014	16,1	88,4	315	20,5	64,4	299	21,5	80,5
5.000 -9.999	1.351	5,4	93,8	167	10,9	75,3	116	8,4	88,9
10.000 -19.999	712	2,8	96,6	114	7,4	82,7	63	4,5	93,4
20.000 -49.999	297	1,2	97,8	91	5,9	88,6	40	2,9	96,3
50.000 -99.999	189	0,8	98,6	62	4,0	92,6	17	1,2	97,5
100.000 999.999	332	1,3	99,9	98	6,4	99,0	32	2,3	99,8
> 1.000.000	11	0,05	100	15	1,0	100	3	0,2	100

Table 2.4: Number of fires for different occupancies (1986-1995)

2.2.4.3 Extent of damage to building

	All			Non-combustible			Combustible		
Fire loss class [CHF]	Sum of losses 10^6 CHF	%	Σ %	Sum of losses 10^6 CHF	%	Σ %	Sum of losses 10^6 CHF	%	Σ %
all	460.935	100	100	192.535	100	100	266.950	100	100
0 - 499	3.315	0,7	0,7	1.293	0,7	0,7	2.005	0,8	0,8
500 - 999	6.007	1,3	2,0	2.955	1,5	2,2	3.026	1,1	1,9
1.000 - 1.999	10.594	2,3	4,3	5.950	3,1	5,3	4.551	1,7	3,6
2.000 - 4.999	18.737	4,1	8,4	10.742	5,6	10,9	7.837	2,9	6,5
5.000 - 9.999	15.556	3,4	11,8	8.741	4,5	15,4	6.630	2,5	9,0
10.000 -19.999	16.325	3,5	15,3	10.068	5,2	20,6	6.090	2,3	11,3
20.000 -49.999	23.978	5,2	20,5	14.106	7,3	27,9	9.603	3,6	14,9
50.000 -99.999	24.028	5,2	25,7	11.662	6,1	34,0	12.133	4,5	19,4
100.000-999.999	245.609	53,3	79,0	97.925	50,9	84,9	147.366	55,2	74,6
> 1.000.000	96.952	21,0	100	29.150	15,1	100	67.802	25,4	100

Table 2.5: Extent of fire damage (in 10^6 Swiss Francs) for different building types (1986-95)

	Dwellings			Industrial			Office / Public		
Fire loss class [CHF]	Sum of losses 10^6 CHF	%	Σ %	Sum of losses 10^6 CHF	%	Σ %	Sum of losses 10^6 CHF	%	Σ %
all	193.884	100	100	66.703	100	100	21.289	100	100
0 - 499	1.994	1,0	1,0	0,054	0,1	0,1	0,078	0,4	0,4
500 - 999	4.030	2,1	3,1	0,159	0,2	0,3	0,308	1,4	1,8
1.000 - 1.999	7.405	3,8	6,9	0,378	0,6	0,9	0,420	2,0	3,8
2.000 - 4.999	12.268	6,3	13,2	1,053	1,6	2,5	0,930	4,4	8,2
5.000 - 9.999	9.411	4,9	18,1	1,153	1,7	4,2	0,820	3,8	12,0
10.000 -19.999	10.044	5,2	23,3	1,624	2,5	6,7	0,892	4,2	16,2
20.000 -49.999	13.711	7,1	30,4	3,458	5,2	11,9	1,449	6,8	23,0
50.000 -99.999	13.139	6,8	37,2	4,255	6,4	18,3	1,139	5,3	28,3
100.000 -999.999	105.993	54,6	91,8	29,605	44,4	62,7	10,663	50,1	78,4
> 1.000.000	16.032	8,2	100	24,890	37,3	100	4,590	21,6	100

Table 2.6: Extend of fire damage (in 10^6 Swiss Francs) for different occupancies (1986-95)

2.2.4.4 Building floor area

The database of the GVB is grouped into occupancy classes. For each class the value at risk (insured capital) is known. To calculate the approximate floor area for each class this value was divided by an estimated average room height and building value per m^3. The estimation of the average room height and building value was based on the experience of the professional loss experts of the GVB.

Code	Occupancy	N° of buildings	Value CHF · 10^9	Height [m]	Value CHF/m^3	Floor Area m^2	%	∅ m^2/ build.
10	Office, public buildings	10.970	25,5	3	650	13.100.000	11	1194
20	Dwellings	161.190	121,3	2,7	600	74.900.000	61	465
30	Farms	84.930	25,6	8	375	8.500.000	7	100
40	Transport (stations, airport ...)	4.300	3,5	2,5	300	4.700.000	4	1093
50	Shops	4.010	6,8	4	700	2.100.000	2	524
60/70	Industrial buildings	5.450 /7.670	7,3 /12,7	5	300	13.300.000	11	1013
80	Hotels	1.780	5,8	3,2	850	2.100.000	2	1180
90	Annex buildings (car parks ...)	62.210	1,5	2,5	350	2.200.000	2	35
	Total	342.510	205,6			120.900.000	100	353

Table 2.7: Estimated floor area per occupancy class calculated from the value at risk of each class and estimated data for room height and value per m^3 for the 1995 data.

2.2.4.5 Fire occurrence and fire growth

On the basis of the number of fire losses reported to the GVB (Tables 2.3 and 2.4) and the estimated floor areas per occupancy class (Table 2.7) the fire occurrence rate per m^2 per year and the probability of fire spreading to a certain size (loss size) can be deduced. They are given in Table 2.8.

Loss size	All [10^{-6}] / (m^2 • year)	Dwellings [10^{-6}] / (m^2 • year)	Office / Public [10^{-6}] / (m^2 • year)	Industrial [10^{-6}] / (m^2 • year)
All losses	32,3	33,3	10,60	11,6
> 499	22,3	23,7	8,44	10,1
> 999	15,4	16,24	6,60	8,47
> 1.999	9,18	9,22	4,35	6,48
> 4.999	4,19	3,86	2,07	4,11
> 9.999	2,33	2,06	1,18	2,86
> 19.999	1,37	1,11	0,70	2,00
> 49.999	0,927	0,710	0,40	1,32
> 99.999	0,641	0,460	0,27	0,85

Table 2.8: Frequency of fire occurrence and growth to a given loss size [per m^2 • year] for different occupancy classes (1986-1995)

Note: By comparison DIN 18230 (draft 1996: $p_1 = 10 \cdot 10^{-6}$ /($m^2 \cdot$ year) as the probability of fire occurrence for industrial buildings and $p_2 = 0,1$ as the probability of flash over in relation to fire brigade present given occurrence of fire)

2.2.5 FIRE BRIGADE DATA OF BERNE

Only 20 % of all fire brigade attendance are during the period 1989 to 1996 (nine years) were related to fighting building fires. The other attendance's were related to false alarms by automatic detection systems (e.g. of the 679 alarms transmitted by automatic detection systems to the fire brigade from the city of Berne in 1995, 620 or 91,3 % were false alarms) or for other reasons (see Table 2.9).

	Canton of Berne 1988 - 1996		City of Berne 1995	
Reason for action	Number	%	Number	%
Fire	13.921	19,4	313	13,8
Water	8.505	11,9	214	9,4
Forest fires	568	0,8	---	---
Snow	135	0,2	---	---
Oil/Gas/Chemicals	5.256	7,4	105	4,6
Electricity	1.001	1,4	---	---
Traffic accidents removal of scars	1.837	2,6	132	5,8
Others (false alarms, rescue of animals, swarms of bees, search for missing persons, elevators, opening of doors etc.)	40.441	56,4	1.502	67,5

Table 2.9: Number of actions of the fire brigades of Berne and their causes (1988-96)

From the survey of large losses (> 100.000 CHF) from 1986 to 1991) [1] the influence of the time from the first alarm to the first action at the site (attendance time) on the extent of losses was analysed. It shows that the extent of damage is very much dependent on the attendance time of the fire brigade.

Attendance time of fire brigade	under 5 minutes	under 10 minutes	exceeding 10 minutes
Distribution of major losses (ML) (> 1.000.000 CHF each) [%]	31	37	32
Major loss quotient (MLQ) = (Major loss amount/insured value) [%]	14	19	39

Figure 2.4: Influence of attendance-time of fire brigade on loss level (losses > 100.000 CHF, 1986 to 1991)

Age of building	After 1949	From 1919 to 1945	**Before 1919**
Distribution of the insured capital (IC) [%]	79	12	**9**
Distribution of major losses (ML) (> 100.000 CHF each) [%]	28	12	**60**
Major loss quotient (MLQ) = (Major loss amount/insured value) [%]	10	35	**35**
Global loss burden = (GL) / (IC) [‰]	0,16	0,30	**1,80**

Figure 2.5: Influence of the age of a building on fire losses (losses > 100.000 CHF, 1986 to 1991)

2.3 ANALYSIS AND INTERPRETATION OF DATA

For the application to fire safety engineering the data given in chapter 2.2 needs to be accompanied by some background information. The following explanations reflect the situation in the canton of Berne and are intended to help the engineer to apply them in other situations.

2.3.1 FIRE OCCURRENCE

The frequency of fire occurrence is given in Table 2.8. There is a difference in fire occurrence between dwellings and industrial buildings. Data on fire occurrence can be obtained from several sources [13, 14, 15, 16] but for purposes of comparison the minimum size of fire which is considered as a fire has to be clearly defined: Does charring constitute a fire? What flame height or heat release or damage amount is needed to make a fire large enough to be counted in statistics?

From the data of the fire brigade it can be seen that the fire brigade is called out to only 40 % of all fires reported in the GVB statistics (Table 2.3 vs. Table 2.9). Therefore the fire occurrence rate from fire brigade reports is smaller than that calculated from the GVB insurance reports.
A comparison of the GVB data of fire occurrence to data from other countries

In addition to the problem of defining what constitutes a fire, relating the fire occurrence to the floor area may not be accurate for small rooms where the utilisation of the room may be more important than the size. This problem cannot be answered by our data, as the size of the room of origin is not included in the database.

2.3.2 FIRE GROWTH

Building costs in Switzerland are high (e. g. dwellings: ~ 600 CHF/m^3 or 1.650 CHF/m^2 gross area). Considering the cost of the building and the data given in Table 2.7, the loss-size classes can be related to the state of fire spread as given in Tables 2.10 and 2.11.

Fire damage to building [CHF]	Number of fires	%	Σ %	Interpretation of fire growth (dwellings)
all	24.962	100	100	
0 - 499	7.204	28,85	28,8	
500 - 999	5.592	22,4	51,2	charring only (non-flaming fire)
1.000 - 1.999	5.260	21,1	72,3	Self-terminated or extinguished by occupants
2.000 - 4.999	4.014	16,1	88,4	
5.000 - 9.999	1.351	5,4	93,8	
10.000 - 19.999	712	2,8	96,6	
20.000 - 49.999	297	1,2	97,8	did not spread beyond room of origin
50.000 - 99.999	189	0,8	98,6	spread beyond room of origin but controlled by fire brigade
100.000 - 999.999	332	1,3	99,9	
> 1.000.000	11	0,05	100	very large spread (total failure in most cases)

Table 2.10: Assumed relation between fire loss size and state of fire growth for dwellings

Fire loss class [CHF]	Number of fires	%	Σ %	Interpretation of fire growth state (industrial buildings)
all	1.538	100	100	
0 - 499	188	12,2	12,2	
500 - 999	223	14,5	26,7	
1.000 - 1.999	265	17,2	43,9	charring only
2.000 - 4.999	315	20,5	64,4	
5.000 - 9.999	167	10,9	75,3	extinguished by staff
10.000 - 19.999	114	7,4	82,7	
20.000 - 49.999	91	5,9	88,6	fire localised by fire brigade
50.000 - 99.999	62	4,0	92,6	
100.000 - 999.999	98	6,4	99,0	
> 1.000.000	15	1,0	100	spread beyond room of origin

Table 2.11: Assumed relation between fire loss size and state of fire growth for industrial buildings

The BSI document DD 240 part 1 "Fire safety engineering in buildings" [3] gives in table B.5 data on the extent of damage due to fires. A comparison of the BSI data with the data from the Canton of Berne (Table 2.3) is given in Table 2.12. The BSI data shows more severe damage than found from our statistics. According to Table 2.3 only about 7,3% of fires cause significant damage (severe damage or destruction e.g. loss over 5.000 CHF) compared to 10,5% in table B.5 of [3].

Extent of damage	BSI	GVB	
	%	[CHF]	%
No damage	70,0	< 1.000	52,3
		< 2.000	71,6
Slight	12,0	2.000 to 4.999	15,4
Surface	7,5	5.000 to 9.999	5,7
Severe	7,5	10.000 to 49.999	4,4
Destruction	3,0	> 50.000	2,9
		> 100.000	2,0

Table 2.12: Comparison of extent of damage from the GVB statistics with BSI [3] for all fires

A comparison of Tables 2.10 and 2.11 and table B.8 of [3] shows a much smaller rate of fires spreading beyond the room of origin in dwellings (2,2% in Berne compared to 10% (day) and 19% (night) in table B.8). For industrial buildings the Berne figure derived from Table 2.11 is 11,4% compared to 12% (day) and 15% (night) given in table B.7 [3]. Excluding the fires causing damage of less than 2.000 CHF the proportion of fires spreading beyond the room of origin increases for the Berne data to 7,7% for dwellings and to 20% for industrial buildings.

2.3.3 SUCCESS OF FIRE BRIGADE

In Switzerland no dwellings and few industrial buildings are equipped with sprinklers. Therefore in the following considerations the few cases where there was successful fire fighting mainly due to sprinklers will be neglected. This simplification will have little influence on the statistical evaluation of the fire brigade success rate, as the number of sprinklered cases is small.

2.3.3.1 All buildings

From Tables 2.3 and 2.9 it can be seen that the fire brigade is called out to only 40 % of all fires reported. As the fire brigade attends all large fires the other fires must have died out by themselves or have been extinguished by the occupants:
Average number of fires per year (1986 - 1995) 39.104 ÷ 10 = 3.910

Average number of fire brigade attendance's for
fires in buildings per year (1988 - 1996) 13.921 ÷ 9 = 1.547

Proportion of fires which require fire brigade action 1.547 ÷ 3.910 = 0,40

A comparison with Table 2.3 shows that this corresponds to the proportion of fires with a loss larger than ~ 1.000 CHF. Smaller fires are usually handled by the occupants.

The success of a fire brigade attendance can be defined on the basis of specific performance goals. One goal is to limit the fire growth to the room of origin. In Swiss dwellings structural damage to the amount of 50.000 CHF corresponds approximately to the value of one room.
The statistics show that the Bernese fire brigade was not successful in reaching that goal in 7,2 % of their attendance's (see Tables 2.3 and 2.9).

$$(346 + 708 + 67) \div [13.921 \bullet (10 / 9)] = 0{,}072$$

In other words in 93,8 % of their attendance's the Bernese fire brigade was successful in confining the fire to the room of origin (or damage to the structure of less than 50.000 CHF).

While the overall probability of a fire spreading out of the room of origin is:

$$1.121 \div 39.104 = 0{,}0287$$

2.3.3.2 Industrial buildings

For 44 % of the fires in industrial buildings the loss did not exceed 2.000 CHF (Table 2.4: 676 ÷ 1.538 = 0,44) and in 7 % of the cases (113/1.538) the loss is larger than 100.000 CHF. If one assumes that all fires would self-terminate or be extinguished by the occupants if their reported loss is less than 2.000 CHF and that the fire brigade is successful if their loss is smaller than 100.000 CHF, then the fire brigade is not successful in 13 % of industrial fires (113 / (1.538 - 676) = 0,13) or for a target of 50.000 CHF maximal loss the fire brigade is not successful in 20 % of the cases.

The German standard DIN 18230 gives a reduction factor for the probability that a fire will get out of control for the fire brigade $p_2 = 0{,}1$. The background document [16] relates this number to an average compartment size of 2.500m^2.

2.3.3.3 Dwellings

In dwellings fire damage did not exceed 2.000 CHF in 72 % (18.056 ÷ 24.962 = 0,72). In 2 % of all cases it exceeded a damage of 50.000 CHF (532 ÷ 24.962 = 0,02). From this data it can be assumed that the fire brigade is not successful in 7,7 % (532 ÷ [24.962 - 18.056] = 0,077) of all attendance's. This result is close to the value found above on the basis of the fire brigade reports. The fire brigade seems to be roughly 3 times more successful in dwellings than in industrial buildings in limiting the damage to less than 50.000 CHF - probably due to smaller compartmentation in dwellings.

2.3.4 SUCCESS IN LIMITING FIRE GROWTH

From Tables 2.8, 2.3, 2.10 and 2.11 some interpretation of the success to limit fire growth can be drawn which is given in Table 2.13. For the application of such data some examples are given in chapter 6.

	All	Dwellings	Office / Public	Industrial
occupants fire loss smaller than 1.999 CHF	71,6 %	72,3 %	59,0 %	43,9 %
fire brigade percentage of all the fires that don't grow over a loss of 49.999 CHF if loss > 1.999 CHF	89,9 %	92,1 %	90,8 %	79,7 %
fire brigade percentage of all the fires that don't grow over a loss of 99.999 CHF if loss > 1.999 CHF	92,9 %	95,0 %	93,8 %	86,7 %

Table 2.13: Success of limiting the fire growth

2.4 CASUALTIES RELATED TO FIRES IN BUILDINGS IN THE CANTON OF BERNE (1986 - 1995)

2.4.1 GENERAL ANALYSIS OF DATA

A general survey of all casualties due to fire (not only in buildings) for the Canton of Berne based on GVB-data for 1986-95 is given in Table 2.14a:

Year 1986 - 1995	fatalities	5 year average	10 year average	fatalities in dwellings	5 year average	10 year average	injuries
1986	1	2,2		1	1,8		14
1987	0	1,6	1,8	0	1,4	1,5	10
1988	3	1,0	1,6	3	0,8	1,3	12
1989	4	1,0	1,8	2	1,0	1,5	9
1990	4	1,6	2,1	4	1,2	1,6	9
1991	4	2,4	2,3	3	2,0	1,9	25
1992	6	3,0	2,3	5	2,4	1,9	16
1993	5	4,2	2,6	5	3,4	2,1	18
1994	7	4,6	2,8	7	3,8	2,4	22
1995	5	5,2	3,4	4	4,8	3,0	24
Total	39			38			159

Table 2.14a: Survey of fire related casualties for the Canton of Berne (1986 - 95, GVB-data)

In 1995 the number of people living in the Canton of Berne was 0,950 Mio. The average of fatalities over the period 1986 - 1995 for all of Switzerland is 4,7 persons / 10^6 people / year which is slightly higher than the Berne values (3,9 persons / 10^6 people / year). The Swiss fire fatality rate is low in comparison to international standards (7 to 25 people per year and 10^6 inhabitant's [4]).

A detailed survey of all fires in buildings in the Canton of Berne, which caused casualties and a damage > 0,1 Mio. CHF was established for the period of 1986 - 1995. Detailed data is given in Table 2.17.

	number of cases	casualties total	casualties / cases
cases total	77		
cases with fatalities	21	22	1,05
cases with casualties	61	106	1,74

Table 2.14b : Survey of casualties with building loss > 100.000 CHF at the same time

A comparison of the Tables 2.14a and 2.14b shows that 43% of the fatalities and 33% of casualties are related to fires with only small damage to the building (< 0,1 Mio. CHF).

	1. structural	%	2. detection	%	3. sprinkler	%
total number of cases with casualties	74	96,1	2	2,6	1	1,2
fatalities	22	100	0	0	0	0
casualties	92	86,8	12	11,3	2	1,9

Table 2.15a: Casualties with regard to the fire safety concepts

The canton of Berne has approximately 500 buildings with sprinkler protection and 1.500 with detection (of 335.000 in total).

code	occupancy	casualties		Number of casualties (killed or injured)		
		fatalities	injuries	1. structural	2. detection	3. sprinkler
10	public and office	3	15	6	12	
20	dwelling	17	52	67		2
30	agricultural	2	23	25		
40	public transportation					
50	shops		2	2		
60	industrial and commercial works		10	10		
80	hotels and restaurants		4	4		
	total	22	106	total 128		

Table 2.15b: Casualties for different occupancy classes

2.4.2 FIRE FATALITIES IN BERNE AND OTHER COUNTRIES

Figures 2.6a to 2.6d show the number of fatalities in building fires for Berne (data from the Swiss Federal Office of Statistics 1970 - 1994) [21] and Australia (CSIRO data 1989 - 1993) [22]. It can be seen that males are over-represented in the fire fatalities. This situation does not exist uniformly through the entire age range. Up to the age 15 and above age 70 the differences are smaller. In the Australian database the children aged among 0 and 5 are significantly over-represented, even more so are people aged 65 and above for both countries.

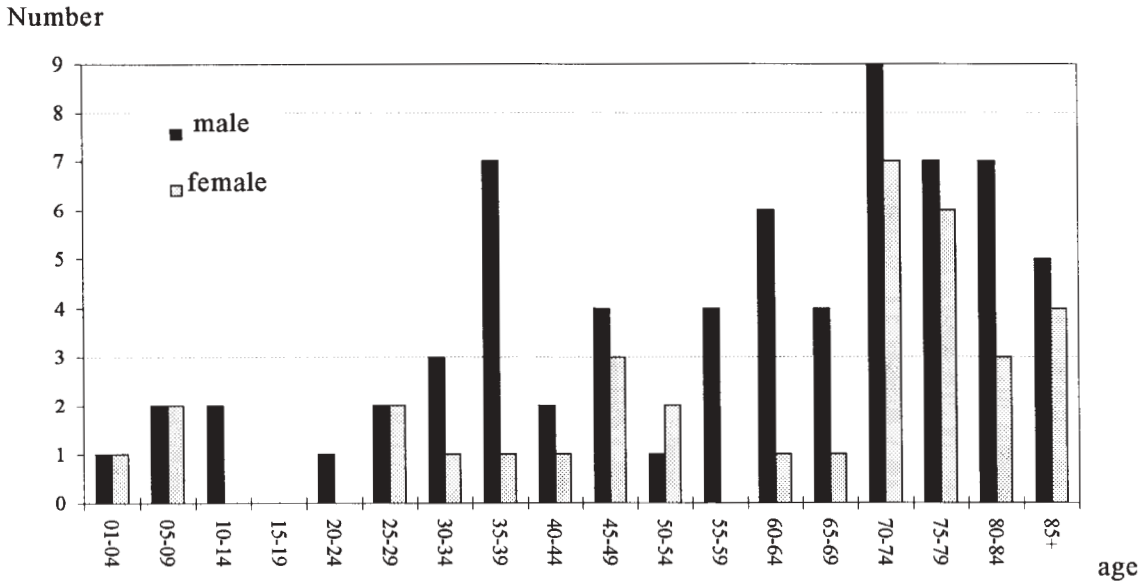


Figure 2.6a: Fire fatalities by age and sex in the Canton of Berne (1970-1994) [21]

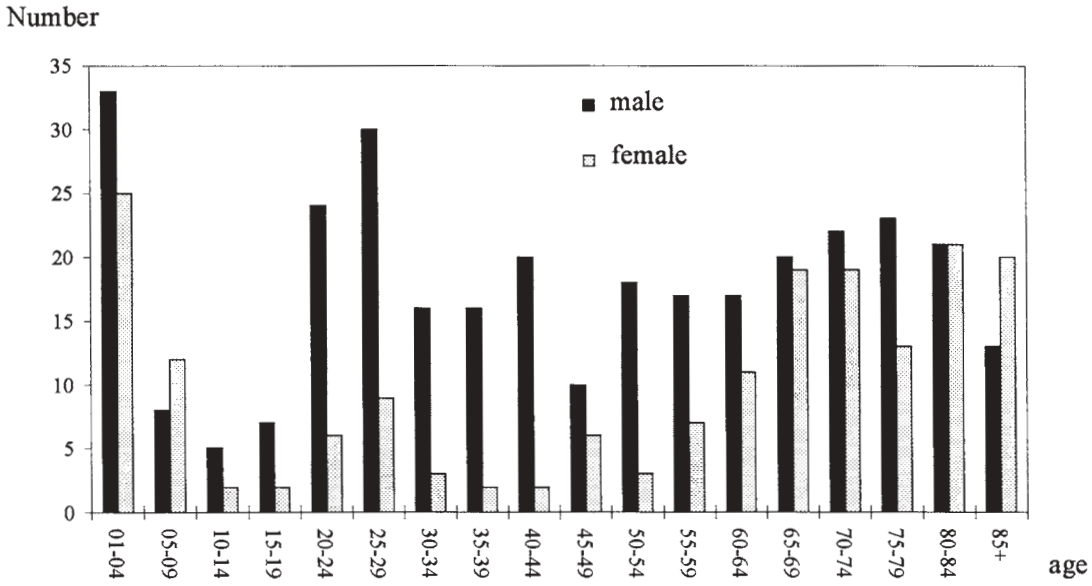


Figure 2.6b: Fire fatalities by age and sex in Australia (1989-1993) [22]

In Figure 2.6c the development of the fire fatalities in the Canton of Berne during the period 1970 - 1994 given by the Swiss Federal Office of Statistics are shown [21]. Male fatalities are dominant.

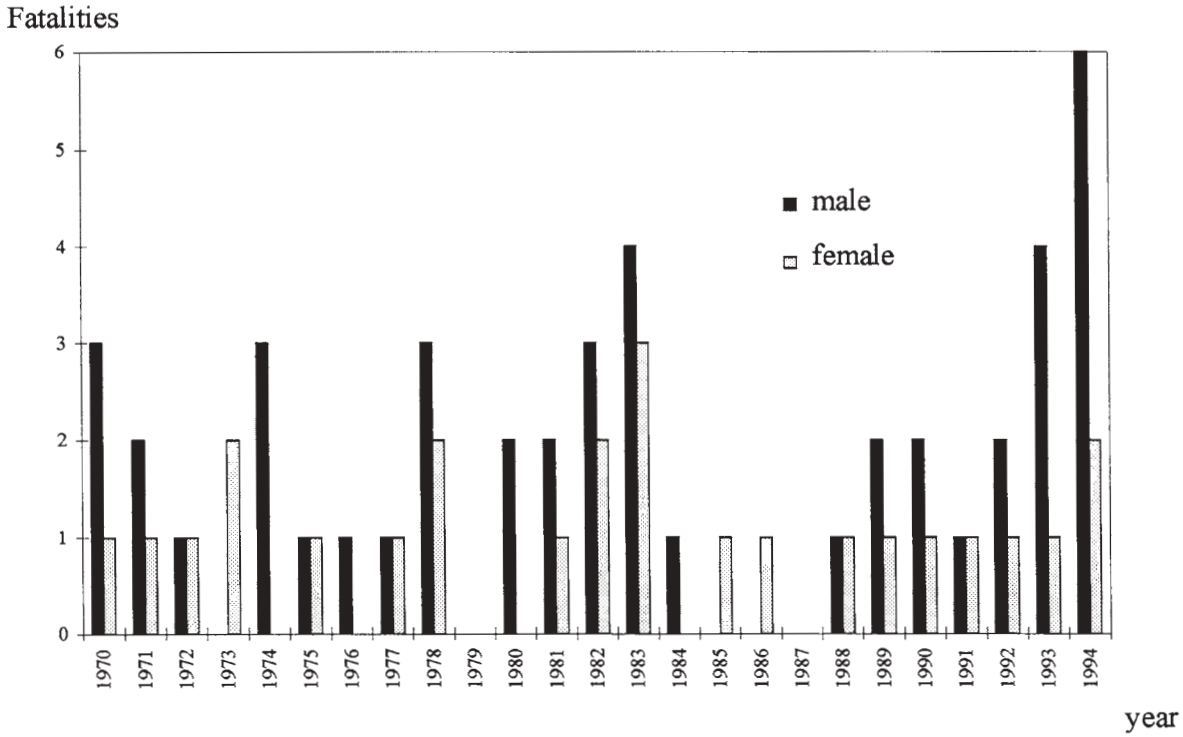


Figure 2.6c: Fatalities in function of the sex in the Canton of Berne (1970-1994)[21]

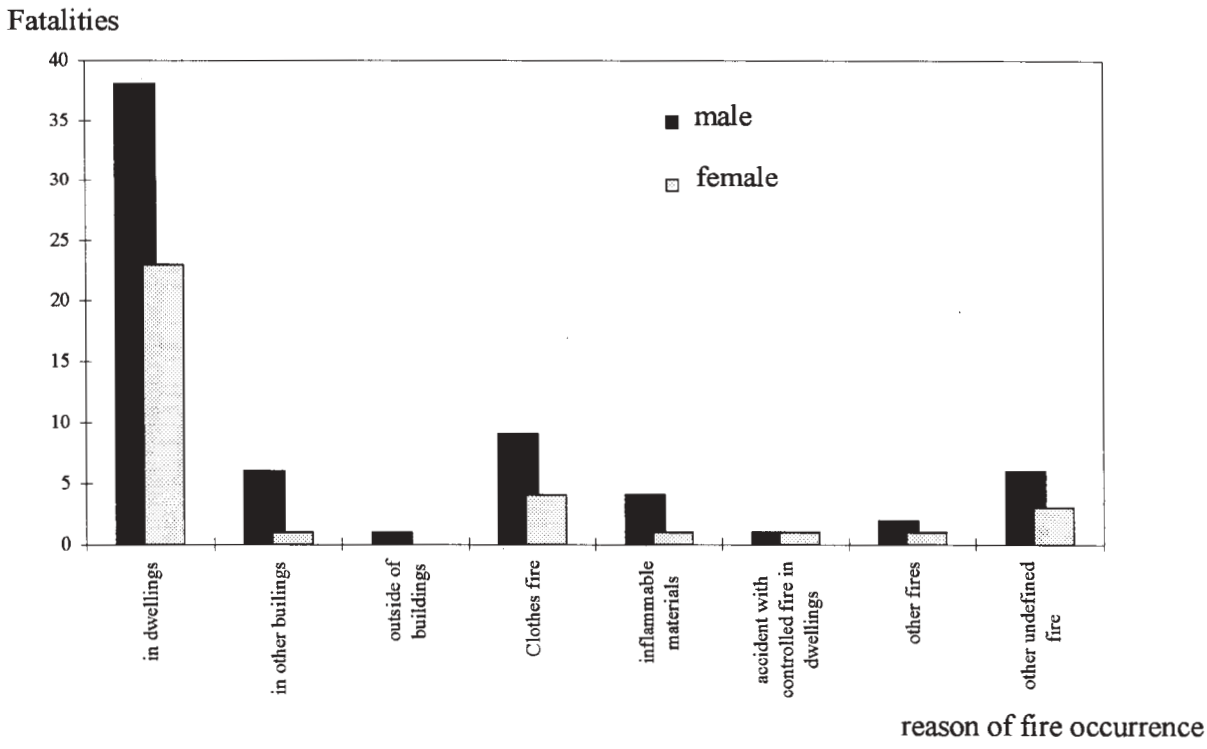


Figure 2.6d: Fatalities in function of the cause of fire occurrence in the canton of Berne (1970-1994, the source is Swiss Federal Office of Statistics) [21]

Looking at the reason of the fatalities in fires it can be seen that over 56 % of all male and over 67 % of all female fatalities occur in dwellings. The group "other fires" includes all with known causes but not belonging to the first six categories, the group "other undefined fires" contains all the fires with missing information.

code of occupancy	fatalities time of day 24.^{00}-06.^{00}	06.^{00}-16.^{00}	16.^{00}-24.^{00}	Σ	injuries time of day 24.^{00}-06.^{00}	06.^{00}-16.^{00}	16.^{00}-24.^{00}	Σ
10		3		3		8	7	15
20	7	5	5	17	18	21	13	52
30			2	2	10	10	3	23
40								
50					2			2
60					2	6	2	10
80					1	2	1	4
	7	8	7	22	33	47	26	106

Table 2.16: Occupancy classes and daytime

The survey shows again, that most people are killed in dwellings (77% of cases accompanied by building losses > 100.000 CHF given in Table 2.10). Nobody was killed in a building with active fire safety systems (Table 2.15) (for French data see 3.1.2.7).

2.4.3 ANALYSIS OF FIRE FATALITY DATA WITH SWISS RISK EVALUATION METHOD SIA DOC 81.

The application of the Method SIA DOC 81 [44] implies that the general regulations for the escape routes are respected. Therefore, no grading of the escape facilities and smoke venting is implemented. Further the method aims mainly at the fire safety of large buildings like industrial premises and public buildings. Therefore the general application to fires with casualties does not seem to be appropriate, as 86% of the fires with fatalities were due to fires in dwelling or farm houses.

The number of people killed in a fire was set in relation to the fire safety index γ. As expected no correlation be found, even if the number of fatalities is set in relation to the number of people present in case of fire outbreak. However, for the cases with injuries in industrial premises all buildings had a safety index smaller than 1.0. No fatality occurred in fires in any of the industrial buildings.

The three people killed in public buildings were one prisoner, one pilot that flew into a church and one person in a storage room. Therefore, no correlation to the γ factor can be established.

Most of the fatalities occurred in fires where the loss was very small (e.g. no fire spread out of the room of origin). In these cases better compartmentation or fire resistant structures would not have been beneficial.

Analysis of the fires of the canton Bern / loss > 0.1 Mio. CHF

loss statistic with casualities and fatalities

loss specific informations									casualities			building informations				CHF	CHF	%	CHF	CHF	CHF	cause of loss			deficiency				modi-fied	fire risk evaluation according to SIA-Dok.81								
damage-number	occupancy	no. of floors	city	cause	fire origin	time of day	day	estimated number of people in building	fatalities N°	cause of death	injuries N°	type	material	age	concept	Insured building value	building damage	damage / value	damage contents	damage total	transf. loss neigh-bour building	% fire	% smoke	% water	passive prot.	electr	fire brig.	fire water		γ	P	N	S	F	A	B	R	R-Gr.
6026001	31	1	Reiniswil	91	room	1	4	7			2	V	2	1815	1	0.63	0.62	0.99				80	10	10	6		5	U	yes	0.13	3.85	0.50	0.80	1.00	1.00	9.63	9.63	1.30
6038030	20	4	Bern	41	floor	14	7	18	2	S/H	7	G	4	1876	1	0.44	0.44	1.00				80	20				*		yes	1.31	2.18	1.00	1.60	1.38	1.00	2.99	0.99	1.30
6158003	25	3	M'buchsee	19	garage	14	4	5			2	G	3	1959	1	0.92	0.17	0.19				50	40	10	6		*		yes	1.94	1.69	1.00	1.40	1.79	1.00	0.67	0.67	1.30
6193004	32	1	Reichenbach	53	stable	22	4	1			1	V	2	1929	1	0.17	0.18	1.03				70	20	10	6		5		yes	0.41	2.65	0.77	1.08	1.00	1.00	3.19	3.19	1.30
7006006	20	4	Lyss	22	room	1	5	12			1	G	4	1880	1	1.03	0.79	0.77				50	10	40			*		yes	0.91	2.40	1.00	1.40	1.20	1.00	1.43	1.43	1.30
7382001	14	4	Belp	49	handicraft	11	4	18			5	G	4	1939	2	3.75	0.80	0.21				40	40	20			*		yes	1.44	2.48	1.00	2.44	1.32	1.00	0.77	0.77	1.30
7464009	20	3	Sumiswald	21	room	10	4	9			2	V	2	1870	1	0.71	0.45	0.62				60	10	30			5	U	yes	0.30	3.24	0.71	1.08	1.00	1.00	4.29	4.29	1.30
8229004	20	2	Konolfingen	53	eitchen	21	2				2	V	5	1922	1	0.34	0.23	0.67				60	30	10	6				yes	0.90	1.56	1.00	1.00	1.08	1.00	1.44	1.44	1.30
8419003	31		Diemtigen	71	front	18	3	4	1	ü		V	2	1679	1	0.12	0.12	1.04			0.12	80	10	10				U	yes	0.19	3.85	0.52	0.92	1.00	0.85	8.05	6.84	1.30
8452004	20	2	Thun	22	room	17	3	6			1	Z	3	1947	1	0.50	0.20	0.39				60	30	10			*		yes	2.45	1.32	1.00	1.40	1.79	1.00	0.53	0.53	1.30
9038091	32		Bern	51	treshing	4	7	2			1	V	2	1900	1	0.12	0.12	1.00				80	10	10	6		*		yes	0.70	2.96	1.00	1.60	1.00	1.00	1.85	1.85	1.30
9041005	20		Kirchlindach	91	room	3	4	3			1	G	3	1977	1	0.44	0.37	0.86				70	10	20			5		yes	1.83	1.72	1.00	1.35	1.79	1.00	0.71	0.71	1.30
9106002	20		Vauffelin	91	floor	22	2	2	1	H		V	2	1967	1	0.69	0.65	0.95				80	20	20					yes	0.87	1.72	1.00	1.15	1.00	1.00	1.50	1.50	1.30
9382016	10		Belp	51	warehouse	8	4	7	1	R		G	2	1975	1	0.15	0.16	1.06				80	10	10			*		yes	0.60	3.00	1.00	1.40	1.00	1.00	0.86	0.86	1.30
9487001	31		Wallirwl-Bipp	51	room	7	5	5			2	V	2	1827	1	0.47	0.47	1.00				80	10	10	8	2			yes	0.34	3.85	1.00	1.00	1.00	1.00	3.85	3.85	1.30
0021012	73		Langenthal	91	front	24	5	3			1	V	5	1910	1	0.15	0.16	1.06			0.06	80	10	10			*		yes	1.00	2.18	1.00	1.40	1.20	1.50	2.30	1.30	1.30
0043047	31		Muri	51	floor	20	2	4			1	V	2	1825	1	0.40	0.40	0.99				80	10	10	2		*		yes	0.62	2.96	1.00	1.40	1.00	1.30	2.11	2.11	1.30
0049040	20		Biel	71	garage	21	7	12			2	Z	3	1971	1	2.57	0.15	0.06				10	80	10	2		*		yes	1.69	2.18	1.00	1.45	1.94	1.00	0.77	0.77	1.30
0145002	26		Bätterkinden	91	room	7	2	7	1	R		G	3	1932	1	0.60	0.50	0.84				40	20	40			*		yes	1.41	1.87	1.00	1.35	1.50	1.00	0.92	0.92	1.30
0322010	21		Port	22	room	3	7	5	1	H		G	4	1960	1	0.52	0.30	0.57				30	40	30			*		yes	1.67	1.45	1.00	1.35	1.38	1.00	0.78	0.78	1.30
1021019	73	4	Langenthal	24	roof	14	1	50			1	V	2	1915	1	45.0	2.40	0.05				50	40	10	2.7		*		no	0.42	3.42	1.00	1.60	1.32	1.20	2.59	3.12	1.30
1021034	66	1	Langenthal	41	heater	17	1	11			1	G	2	1946	1	1.45	1.19	0.82	2	3.2		70	10	20	2.4		*		no	0.78	2.34	1.00	1.40	1.00	1.00	1.67	1.67	1.30
1038090	28	5	Bern	52	room	1	6	11			1	G	3	1957	1	2.51	0.18	0.07				10	80	10					yes	1.43	2.18	1.00	1.60	1.50	1.00	0.91	0.91	1.30
1041005	26	3	Kirchlindach	52	room	5	7	8			1	G	3	1950	1	2.70	0.60	0.22				40	20	40					yes	0.98	2.22	1.00	1.35	1.79	1.20	0.55	0.66	1.30
1049047	20	8	Biel	22	room	1	3	65			1	V	3	1962	1	4.71	0.21	0.04				20	60	20			*		yes	1.15	2.44	1.00	1.45	1.50	1.00	0.56	0.56	1.30
1078002	14	5	Krauchthal	72	cell	16	2	45	1	H		Z	3	1895	1.2	6.45	1.62	0.25				50	40	10				U	no	0.97	2.21	1.00	1.45	1.82	1.00	0.87	0.87	1.30
1265002	20	2	Möhleberg	12	room	22	2				1	G	5	1850	1	0.39	0.39	1.00				80	10	10					yes	1.34	1.72	1.00	1.35	1.32	1.00	0.97	0.97	1.30
1382010	11	4	Belp	91	room	12	2				2	V	3	1972	1	2.40	0.27	0.11				10	70	20					yes	1.40	1.95	1.00	1.40	1.50	1.00	0.93	0.93	1.30
1042006	66	1	Etenbach	24	hall	12	4	12			2	G	2	1944	1	1.43	1.26	0.88			0.10	70	10	20	6.7		1		no	0.75	1.87	0.80	1.35	1.00	1.00	1.73	1.73	1.30
1428003	81	2	Lenk	91	barn	8	2	50			2	V	2	1850	1	1.08	1.09	1.01				90	10		2.6		5	U	yes	0.33	2.64	0.50	1.35	1.00	1.00	1.55	1.55	1.30
1464005	20	1	Sumiswald	24	roof	16	3				1	G	3	1959	1	0.86	0.11	0.12				40	10	50					yes	2.00	1.32	1.00	1.35	1.50	1.00	0.56	0.56	1.30
1494005	20	3	Bern-Bümpliz	22	floor	4	3	5			1	V	3	1947	1	0.79	0.18	0.22				30	40	30			*		yes	1.33	2.34	1.00	1.60	1.50	1.00	0.98	0.98	1.30
1494008	20		Bern-Bümpliz	20	room	4	6	9	1	R	1	V	4	1900	1	0.47	0.21	0.45				40	20	40			*		yes	0.81	3.38	1.00	1.60	1.32	1.00	1.60	1.60	1.30
2006037	12		Lyss	89	roof				1	pilot dead before the fire in the church																												
2038017	21		Bern	53	eitchen	4	3	32	1	R	2	G	3	1974	1	12.3	0.33	0.03				20	70	10			*		yes	1.43	2.18	1.00	1.60	1.79	1.00	0.91	0.91	1.30
2038038	26	4	Bern	22	room	7	2	22	1	H		V	4	1800	1	2.64	2.40	0.91				40	20	40	2.7	nein	*		no	0.74	1.78	0.72	1.60	1.32	1.20	1.17	1.41	1.30
2038161	14	3	Bern	91	room	21	1	90			7	G	3	1948	2	14.6	0.21	0.01				20	70	10			*		yes	2.42	2.06	1.00	2.78	1.72	1.00	0.22	0.22	1.30
2049014	29	4	Biel	73	stairs	21	7	13	1	S	2	G	3	1890	1	1.62	0.72	0.44				10	70	20			*		yes	1.97	1.58	1.00	1.45	1.72	1.00	0.63	0.63	1.30
2049053	80	5	Biel	72	restaurant	2	3	90			1	G	3	1921	1	3.78	0.60	0.16				10	80	10			*		yes	1.07	2.38	1.00	1.45	1.50	1.00	0.44	0.44	1.30
2049087	28	4	Biel	22	restaurant	7	1				6	G	3	1963	1	1.94	0.89	0.46				30	40	30			*		yes	1.19	2.18	1.00	1.45	1.38	1.00	1.09	1.09	1.30
2285005	66	1	Malleray	73	silo	4	1				2	G	5	1954	1	0.91	0.94	1.02				80	10	10	4				no	0.50	2.15	1.00	1.00	1.00	1.00	2.58	2.58	1.30
2398002	31	2	N'muhlern	72	treshing	18	6	6			1	V	2	1951	1	0.56	0.58	1.03				80	10	10					yes	0.41	3.65	1.00	1.15	1.00	1.00	3.17	3.17	1.30
2401024	26	2	Rüeggisberg	19	workshop	23	3	4			1	G	5	1945		0.29	0.30	1.02				80	10	10			2	U	yes	0.18	2.18	0.45	0.80	1.00	1.20	6.06	6.06	1.30
2449005	20	3	Steffisburg	51	room	17	1	8	1	U		G	3	1946	1	1.05	0.43	0.41				40	20	40			*		yes	1.59	1.72	1.00	1.40	1.50	1.00	0.82	0.82	1.30
2494003	29	3	Bern-Bümpliz	24	workshop	9	4	7			2	G	3	1931	1	2.51	0.64	0.26				40	40	20			*		yes	0.83	3.14	1.00	1.60	1.50	1.20	1.31	1.31	1.30
3013015	20	2	Aarwangen	52	room	1	4	2			2	V	3	1956	3	0.24	0.20	0.80				20	60	20					yes	2.28	1.56	1.00	1.30	2.09	1.00	0.57	0.57	1.30
3038047	20	4	Bern	22	room	1	6	8	1	R		Z	3	1957	1	1.26	0.15	0.12				20	60	20			*		yes	2.24	1.98	1.00	1.60	2.14	1.00	0.58	0.58	1.30

Table 2.17: Number of fatalities compared to the safety index γ

3057001	29	1	Langnau	51	restaurant	4	5	14			2	G	4	1900	1	0.93	0.82	0.88			1.40	80	10	10					yes	1.30	1.89	1.00	1.30	1.45	1.00	1.00	1.00	1.30
3196004	32	1	Brienz	51	stable	12	6	0			2	G	2	1890	1	0.23	0.19	0.83				80	10	10					yes	0.73	2.81	1.00	1.35	1.00	0.85	2.08	2.08	1.30
3199023	20	2	Grindelwald	52	room	7	5*				1	V	2	1865	1	0.96	0.10	0.10				30	50	20					yes	0.95	2.03	1.00	1.35	1.10	1.00	1.37	1.37	1.30
3380003	20	2	Rüschegg	53	citchen	23	2	3	1	R		Z	4	1972	1	0.32	0.22	0.68			0.02	30	40	30					yes	2.50	1.32	1.00	1.15	2.22	1.00	0.52	0.52	1.30
3410065	73	1	Langnau	82	workshop	14	2	7			1	G	1	1957	1	1.11	0.45	0.40				60	20	20					yes	0.61	2.42	1.00	1.35	1.00	1.28	1.07	1.07	1.30
3449018	20	2	Steffisburg	22	room	21	5	3	1	R	1	V	5	1900	1	0.46	0.26	0.56				30	40	30					yes	0.93	2.03	1.00	1.40	1.00	1.00	1.45	1.45	1.30
3460001	29	2	Eriswil	51	office	6	7	2			2	V	2	1800	1	0.92	0.95	1.03			0.01	80	10	10			4		yes	0.57	2.64	1.00	1.15	1.00	1.00	2.30	2.30	1.30
4006032	20	4	Lyss	23	room	4	7	17	1	R		G	3	1970	1	2.16	0.38	0.18				20	70	10			*		yes	1.97	1.98	1.00	1.40	2.14	1.00	0.66	0.66	1.30
4011001	20	2	Schüpfen	16	balcony	14	7	4			1	V	5	1860	1	0.66	0.57	0.86				60	10	30					yes	1.07	2.18	1.00	1.50	1.32	1.00	1.22	1.22	1.30
4038228	20	2	Bern	23	room	4	4	5	1	R		Z	3	1927	1	0.48	0.14	0.29				20	70	10					yes	3.10	1.32	1.00	1.60	1.97	1.00	0.42	0.42	1.30
4038233	10	6	Bern	23	mansard	10	5	35			1	G	3	1908	1	3.12	0.52	0.17				10	70	20			*		yes	1.57	1.98	1.00	1.60	1.50	1.00	0.33	0.33	1.30
4301003	20	5	Tavannes	52	flat	4	3	18	1	R		Z	3	1929	1	1.60	1.29	0.81				20	60	20	2				no	1.33	1.98	1.00	1.35	1.32	1.00	0.57	0.57	1.30
4382007	20	2	Belp	22	room	22	1				1	Z	3	1971	1	1.60	0.15	0.10				20	70	10			*		yes	3.42	1.32	2.00	2.50	1.50	1.00	0.39	0.39	1.30
4416001	31	1	Trub	15	room	16	7	3	1	H		V	2	1850	1	0.53	0.55	1.04				80	10	10					yes	1.34	1.12	1.00	1.15	1.00	1.00	0.97	0.97	1.30
4429005	26	2	St. Stephan	53	citchen	15	7	3	1	R		V	2	1700	1	0.43	0.39	0.91				60	10	30					yes	0.94	1.87	1.00	1.35	1.00	1.00	1.39	1.39	1.30
4478001	31	2	Niederbipp	52	treshing	5	2	6			1	V	5	1850	1	0.24	0.26	1.07				80	10	10			*		yes	0.71	2.55	1.00	1.40	1.00	1.00	1.82	1.82	1.30
5212001	71	1	Oberried	42	factory	15	3	1			1	Z	3	1961	1	0.14	0.14	0.94			0.03	100							yes	0.94	1.60	1.50	1.00	2.09	1.80	0.31	0.56	1.30
5259001	31	2	Kriechenwil	51	treshing	11	7	3			2	V	2	1840	1	1.10	1.16	1.05				80	10	10	2.6		5	U	no	1.02	1.46	1.00	1.15	1.00	1.00	1.27	1.27	1.30
6260003	31	3	Fernbalm	81	stone floor	3	4				3	V	2	1902	1	1.50	1.26	0.84				70	10	20	2	2			no	1.47	0.81	1.00	0.92	1.00	1.00	0.88	0.88	1.30
7187003	80	6	Adelboden	81	room	20	4				1	V	5	1910	1	2.80	2.58	0.92				90		10	6.8				no	0.86	1.25	0.72	1.15	1.00	1.00	1.51	1.51	1.30
9314001	31	3	Hermrigen	51	treshing	16	2				1	V	2	1874	1	1.12	1.03	0.92				90		10		2			no	0.64	2.02	1.00	1.00	1.00	1.00	2.02	2.03	1.30
9470001	39	4	Bettenhausen	22	room	11	4				2	V	2	1836	1	3.20	1.08	0.34				30	60	10	1.2				no	1.21	1.28	1.00	1.00	1.20	1.00	1.07	1.07	1.30
42010	31	3	Köniz	51	treshing	1	2				1	V	2	1829	1	1.09	1.12	1.03	0.3	1.4		90		10	2	2			no	1.72	1.24	1.00	1.40	1.00	0.85	0.89	0.76	1.30
1204019	50	4	Interlaken	73	store	3	4				2	V	2	1700	1	1.35	1.07	0.79			1.40	80	10	10	2		5		no	1.01	1.79	1.00	1.40	1.00	1.00	1.28	1.28	1.30
2099002	31	2	Reuan	51	treshing	7	2				1	V	2	1580	1	1.01	1.05	1.04				60	10	30		2			no	1.08	1.37	1.00	1.15	1.00	1.00	1.19	1.20	1.30
3057002	28	3	Langnau	51	transf.	5	5				2	V	5	1900	1	1.72	1.20	0.70				90		10	2				no	1.73	1.28	1.00	1.30	1.32	1.00	0.75	0.75	1.30
4452058	73	2	Thun	82	workshop	14	4				1	G	1	1984	1	2.50	1.45	0.58				60	30	10					yes	0.86	1.77	1.00	1.40	1.00	1.20	1.26	1.52	1.30
4452124	25	4	Thun	53	citchen	17	2				1	V	2	1873	1	0.98	1.05	1.07				50	40	10	1.2				no	1.11	1.80	1.00	1.40	1.10	1.00	1.17	1.17	1.30
4485004	31	2	Seeberg	53	room	2	7				2	V	2	1809	1	1.39	1.46	1.05				90		10					yes	0.56	2.31	1.00	1.00	1.00	1.00	2.31	2.31	1.30
5494006	26	2	Bern-Bümpliz	23	room	2	2	4			1	G	2	1900	1	0.94	0.17	0.18				40	40	20			*		yes	1.02	2.03	1.00	1.60	1.00	1.00	1.27	1.27	1.30

(until 28.8.95)

	people in building	fatalities	injuries
77 cases	806	22	106

damage number		occupancy		cause		cause of death		typ		material		concept		fire protection deficiency		electrical deficiency		Fire brigade deficiency		risk evaluation	
1. figure	year	10-19	Public	10-29	Firing system and fires as directed	R	smoke	Z	small comparments	1	steel	1	structural	1	insufficient fire resistance of structure	1	missing lightning protection	1	insufficient alarm organisation	P	potential danger
2.-4. figure	city code	20-29	Dwellings			H	heat	G	large comparments	2	timber	2	detection	2	insufficient compartmentation	2	missing residual current-switch	2	insufficient means of transport	N	normal measures
5.-7. figure	interna	30-39	Farms	30-39	self lightened	S	fall	V	no compartmentation between floors	3	massiv	3	sprinkler	3	insufficient sealing of ducts	3	supply by roof wiring	3	missing breathing apparatus	S	special measures
	loss number	40-49	Transport	40-49	explosions	E	slay			4	mixed	4	mixed	4	no active measures	4	defective installations	4	insufficient training	F	struct. measures
		50-59	Shops	50-59	electricity	U	other			5	mixed			5	escape route insufficient			5	support unit not requested	A	fire occurance
		60-69	Industrial	60-69	lightning strike						combust.			6	missing fire extinguishers					B	potential loss
		80-89	Hotel	70-79	arson and bomb attack									7	organisational deficiencies					R	effective risk
		90-99	Annex	80-89	other known reasons									8	insufficient maintenance					R-Gr.	accepted risk
				91	unknown reasons																
				98/99	terror and commotion																

Table 2.17 continued: Number of fatalities compared to the safety index γ

3 DATABASE ON REAL FIRES FROM OTHER SOURCES

3.1 FRENCH DATABASE ON REAL FIRES

3.1.1 FIRES IN INDUSTRIAL BUILDINGS

3.1.1.1 Fires in industrial buildings 1983 to 1984

Over a period of 14 months (January 1983 to February 1984), CTICM made an investigation on major fires in commercial and industrial buildings, in collaboration with insurance companies, the Fire Brigade and Home Office [12]. Each recorded fire had resulted in costs higher than 2.000.000 FF (approx. 320.000 ECU). A total of 283 fires with such high damage occurred in France during these 14 months. As an average this means a fire every 36 hours. The fires involved mainly warehouses, department stores and industrial buildings related to clothes, wood or food.

A complete questionnaire was distributed to each fire brigade and insurance company to be filled up in a most precise way. This questionnaire presents 3 main parts: description of the building, description of the fire, description of the damage.

The description of the building is relative to the location (city), the number of storeys, the dimension (surface, height), the type of building structure, its use, the occupancy, the year of construction...

The fire is described in the time domain: time to fire discovery, fire propagation time, fire extinction time, work hours, further information relative to detection or extinction facilities in the buildings, the number of firemen attending the fire, the cause of ignition (criminal, electric, ...) and propagation, and the percentage of the surface and the floors that are either damaged by smoke or by fire. Further comments about weather (strong winds or snow) are given.

The damage is described in terms of financial costs and structures. The costs are divided into damage to building, losses of contents and exploitation time. The structural damages are described in detail: e.g. load bearing structure, roof, compartmentation wall, external walls, suspended ceiling, insulation etc.

Conclusions from all this data have been made. For example, only in 5 cases was an automatic extinction system present, while in 4 of these cases the building was not destroyed. A similar conclusion is made for the automatic detection: only 8 cases had an automatic detection, but the fire surface propagation was half of that than without detection.

This database is available on diskette either as an Access file or as an Excel 5 file. The following Table 3.1a shows the fields used in the database.

Field number	Field name
1	file number
2	information data
3	information organism
4	fire date
5	detection hour
6	average cost of direct damages
7	mean cost of contents
8	department
9	town
10	co-ordinate on Michelin map
11	Co-ordinate on Michelin map
12	building type
13	date of questionnaire sent to the user
14	date of questionnaire sent to the fire brigade
15	global cost
16	load bearing structural cost
17	Cost of contents
18	receipt date of questionnaire by the user
19	receipt date of questionnaire by the fire brigade
20	building visiting date (1 if necessary 9 otherwise)
21	
22	involved surface
23	number of files
24	involved volume
25	zone number
26	building length
27	building width
28	wall height
29	ridge height
30	
31	number of storeys
32	surface of ground level
33	total surface per storey
34	number of burned storeys
35	burned surface of the ground level
36	total burned surface
37	roof type
38	percentage of openings in walls

39	percentage of openings in roof
40	building year
41	building period
42	structure type
43	roof structure type
44	floor type
45	structure anchor type
46	roof covering type
47	translucid bands
48	roof insulation
49	suspended ceilings
50	horizontal partition wall
51	horizontal partition wall structure
52	horizontal partition wall decking
53	external walls
54	insulation of walls
55	wall characteristics
56	compartmentation walls
57	partition wall
58	damage to vertical structure
59	damage to roof structure
60	damage to floor
61	damage to vertical structure anchor
62	damage to roof
63	damage to translucid band
64	damage to insulation
65	damage to suspended ceiling
66	damage to load bearing structure
67	damage to separation surface
68	damage to external walls
69	damage to compartmentation walls
70	damage to partition walls
71	fire insurance company classification
72	global activities in the building
73	classification according R1 rules
74	water rate of sprinklers
75	height between fuel and ceiling
76	classification on severity scale
77	percentage of inflamed surface
78	total surface exposed to fire (all storeys and roof)
79	burned surface on ground level

80	total burned surface
81	burned surface percentage
82	damaged surface percentage
83	number of workers in the company
84	number of workers in the building
85	security team
86	guardian service
87	number of people at fire ignition
88	automatic detection
89	automatic extinction
90	mechanical ventilation
91	vents
92	fire doors
93	fire tap
94	fire extinguishers
95	working hours
96	location of the fire
97	information on the fire
98	cause of fire ignition
99	information on fire ignition cause
100	first combustible
101	propagation between rooms
102	propagation mode
103	fire detection mode
104	fire development state at discovery moment
105	tried to be extinguished by occupants
106	fire development state at the firemen arrival moment
107	firemen inside the building according fire severity
108	firemen inside the building according structure behaviour
109	time of firemen arrival
110	time of firemen intervention beginning
111	time of fire circumscription
112	time of fire mastership
113	time of fire extinction
114	extinction means
115	
116	duration of the fire up to circumscription
117	duration of the fire up to mastership
118	duration of the fire up to extinction
119	
120	cost (building and contents) before fire

121	cost of building before fire
122	cost of contents before fire
123	cost of goods before fire
124	cost of material before fire
125	total cost of damages
126	cost of damages to the building
127	cost of damages to the structure
128	cost of damages to contents
129	cost of damages to goods
130	cost of damages to materials
131	cost and duration of exploitation loss
132	people evacuation
133	problems during people evacuation
134	preliminary evacuation planning
135	total number of injured people
136	total number of dead people
137	number of injured firemen
138	number of dead firemen
139	number of injured occupants
140	number of dead occupants
141	name of occupant or company
142	information about occupant
143	information about occupant
144	information about occupant
145	information about occupant
146	information about occupant
147	name of fire brigade
148	information about fire brigade
149	information about fire brigade
150	information about fire brigade
151	information about fire brigade
152	information about fire brigade
153	name of expert
154	information about expert
155	information about expert
156	information about expert
157	information about expert
158	name of insurance company
159	information about insurance company
160	information about insurance company
161	name of the sinistred industrial building

162	information about sinistred building
163	information about sinistred building
164	information about sinistred building
165	information about sinistred building
166	capa
167	information about rooms
168	information about ground
169	information about walls
170	information about activities
171	information about activities and goods
172	information about goods
173	information about good quantity
174	information about good reparation
175	information about fire severity
176	information about fire development
177	information about fire and rooms
178	information about fire development
179	information about damage
180	observation
181	general remarks

Table 3.1a: Parameters collected in the French survey of industrial fires 1983 to 1984 [12]

3.1.1.2 Level of damage to the structure

The amount of damage to the structure depends on the construction material.

Construction material	damage	N° of cases		%
steel	slight	100	no significant deformations	25,0
	heavy		deformations provokes some reconstruction's	52,0
	total		collapse	23,0
concrete	slight	21	spalling of the corners	67,0
	heavy		cracking	33,0
	total		collapse	-
timber	slight	21	surface damage	9,0
	heavy		start of combustion	33,0
	total		collapse	58,0

Table 3.1b: Damage to the structure for different construction materials

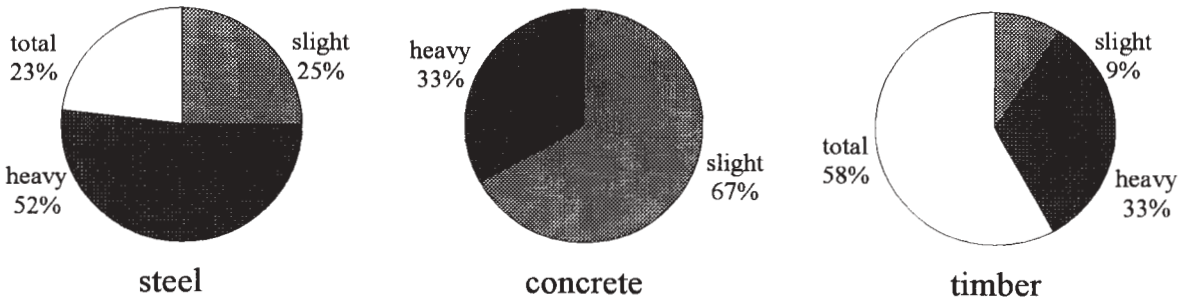


Figure 3.1: Damage to the structure in French industrial buildings (1983 to 1984 and loss > 320.000 ECU)

3.1.2 FIRE BRIGADE DATA ON FIRE OCCURRENCE IN FRANCE

A large statistical database was published in the review 'Face Au Risque' of January 1998 [23], edited by 'Centre National de Prévention et de Protection'. This data is taken from the 'Direction de la Défense et de la Sécurité Civiles' of the French Ministry of Interior which has collected the data from all the 'Directions Départementales d'Incendie et de Secours'. These statistics represent fire brigade intervention in 1995, allowing to define fire occurrence probabilities.
Fire represents only 10% of all the fire brigade intervention (3.253.855 interventions of which 312.910 were for fires). Without taking into account the department out of French metropolis (overseas territories), the numbers are 3.183.897 interventions for which 305.619 were fires. The interventions of the fire brigade are found to be three times higher now than in 1975; also the number of fires is three times higher. In fact, the number of fires was 100.359 in 1975.

3.1.2.1 Activities

The fires are grouped as a function of the activities. Figure 3.2 gives the number of fires per fire type. To show that these numbers are fairly representative of the relevant period, the data for 1994 is also shown. The total number of all fires in Figure 3.2 is smaller than 305.619 because some of the provinces are not taken into account. Nevertheless, the distribution is relatively representative to the global French repartition.
The number of fires in building (public, dwellings and offices, industrial buildings and warehouses) represents only 27 % of all the fire starts. The dwellings and offices are responsible for about 75% of the building fires.

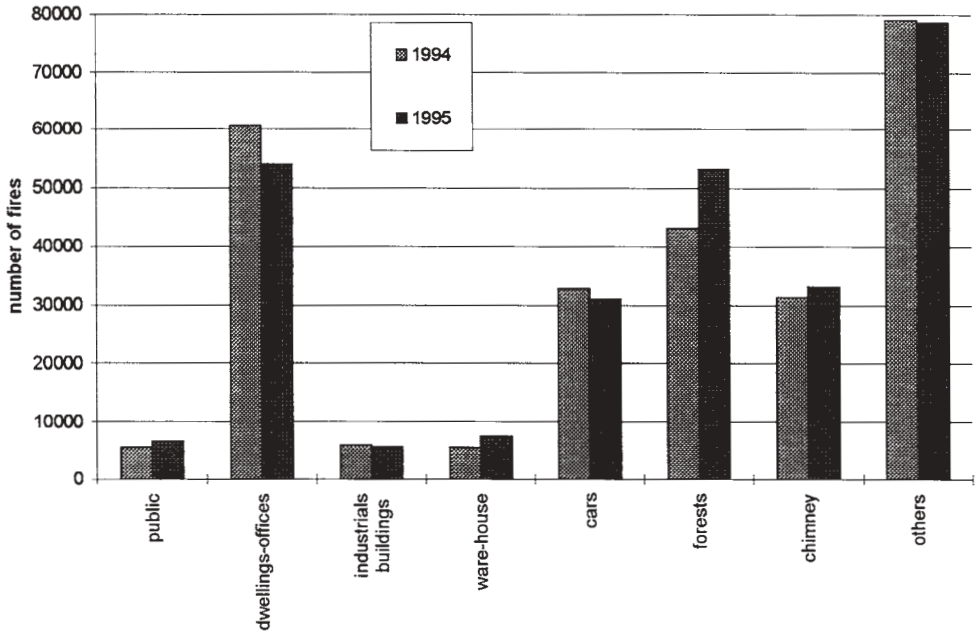


Figure 3.2: Number of fires in function of the activities

3.1.2.2 Fire occurrence per inhabitant

The number of people in France without taking into account the province out of French Metropolis was, in 1995, 55.836.000. Knowing the number of fires to be 305.619, the probability of fire occurrence per inhabitant and per year can be determined:

$$5{,}5 \cdot 10^{-3} \text{ fire starts / people / year (all)}$$

Nevertheless, taking into account the number of fires occurring in buildings, the number of fires is reduced to about 82.000 fires, which indicates a probability of fire occurrence per inhabitant and per year of:

$$1{,}3 \cdot 10^{-3} \text{ fire starts / people / year (in buildings)}$$

3.1.2.3 Fire occurrence per exploitation surface

The exploitation surface per activity is not directly available from French statistics. Nevertheless, some exploitation surface can be estimated from the construction statistics.

For dwellings, the DAEI from the Transports and Housing Ministry gives a total number of dwelling in France of 28 millions. This number will form the basis of our study.

From the Usinor Batimetude data and from the DAEI construction statistics gave the built surface per activity type in 1995 is as shown in Table 3.2.

Activity	Surface (10^3 m^2)
Office	2.740
Industrial building	4.410
Warehouse	3.720
Shops	2.550
Schools	2.160
Sports and culture	1.700
Farming	10.210
Health	1.760
Dwelling	25.637
Total	54.887

Table 3.2: Surface built in 1995 for different occupancies

According to the DAEI of the Transports and Housing Ministry the number of dwellings is 277.130 built in 1995. The ratio gives an average surface by lodging of 92 m^2. So the 28 million of residential buildings represent a living surface of 2.576 million of m^2. Assuming a constant ratio between built surface and total surface for each activity type, it means the ratio for dwellings of about 1%, the total surface per activity can be deduced. This total surface is given in Table 3.3.

Activity	Surface (10^6 m^2)
Office	275,3
Industrial building	443,1
Warehouse	373,8
Shops	256,2
Schools	217,3
Sports and culture	170,8
Farming	1.025,9
Health	176,9
Dwellings	2.576
Total	5.515

Table 3.3: Total surface in 1995

3.1.2.4 Fire occurrence probability per m^2

In order to estimate the fire occurrence probabilities it is necessary to classify the exploitation surface as the classification of the number of fire (see Figure 3.4). This classification is given in 4 classes :

- Public which may include shops, health, sports and culture and schools
- Offices and dwellings
- Industrial buildings which include industrial and farm buildings
- Warehouse

According to this classification and the Figure 3.2, the fire occurrence probabilities can be determined and are given in the Table 3.4.

activity	Surface (10^6 m^2)	Number of fires	Fire occurrence probability ($/10^6$ m^2 / year)
Public	821	7.337	8,9
Offices and dwellings	2.851	60.313	21,2
Industrial buildings	1.469	6.210	4,2
Warehouses	374	8.319	22,3

Table 3.4: Fire occurrence probabilities

3.1.2.5 Comparison with other European values

Some fire occurrence probabilities are estimated in Finland, Switzerland and Germany.

3.1.2.5.1 Industrial buildings and warehouses

For industrial buildings including warehouses, a value of about 10 $/10^6$ m^2/year is deduced. In our French statistics, industrial buildings and warehouses are separated and give different values of 4,2 and 22,3 $/10^6$ m^2/year. Considering a global class including both classifications, the fire occurrence probability is then 7,9 $/10^6$ m^2/year (1.842 millions of m^2 and 14.528 fires). Such a global value is rather close to the other European value.

3.1.2.5.2 Offices and dwellings

Generally, offices and dwellings are separated, giving a highest value for dwellings with a ratio of 3 or 4. Nevertheless, a global class including dwellings and offices is more representative of dwellings for which the number of fires and surface is very high compared to the values for offices. This is why the French value of fire occurrence in offices and dwellings of 22,3 $/10^6$ $/m^2$/year is rather close to the Swiss value for dwellings of 23,7 $/10^6$ $/m^2$/year.

3.1.2.5.3 Public buildings

The French value of fire occurrence in public buildings, 8,9 /10^6 /m^2/year, is relatively close to the values obtained in Finland in hospitals (8,5 /10^6 /m^2/year) and in shops and restaurants (9,5/10^6 /m^2/year) and relatively higher than in Finish schools (3,1 /10^6 /m^2/year). Nevertheless, if it is considered to be a global classification, a very close value may be deduced because the educational buildings represent a small part of the exploitation surface of the global classification.

3.1.2.6 Fire duration

As the duration of the fire is the time from the start of the fire (time of the alarm to the fire brigade) to the moment of the decrease of the intensity of the fire (according the report of the chief of the fire brigade) was taken as the fire duration [12].

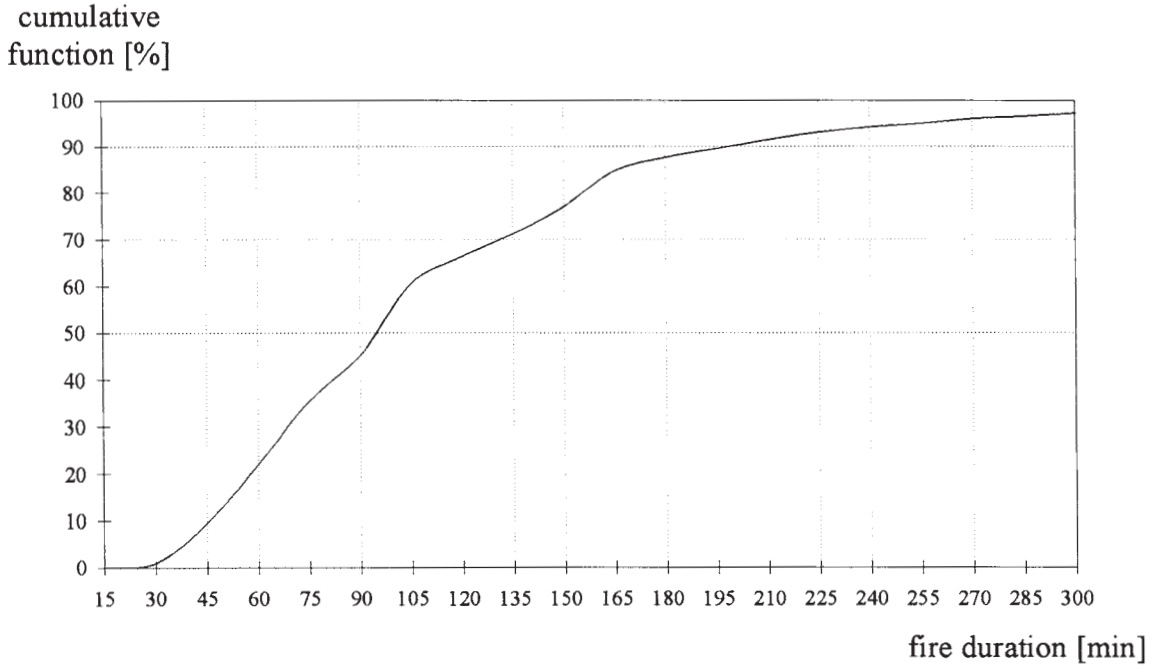


Figure 3.3: Cumulative distribution of the fire duration according to CTICM [12]

3.1.2.7 Fatalities and injuries

In the 312.910 fires 715 people died, 3.282 people were highly injured and 17.416 people were slightly injured. These numbers are also given as a function of the activity, and are given in Figure 3.4. This figure shows that only 236 people died in buildings in 1995, of which about 90% in dwellings/office buildings.

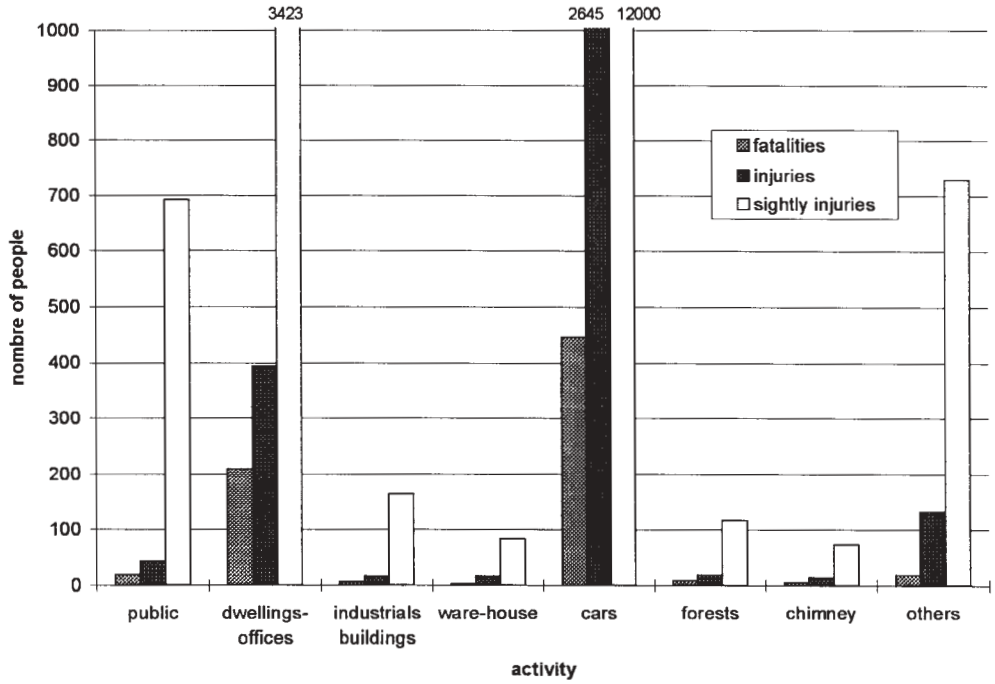


Figure 3.4: Number of injured people according to the building activity in 1995

According to Figure 3.2 and Figure 3.4, the number of fatalities per fire in each activity can be deduced. The Table 3.5 gives these values.

activity	Number of fire in 1995	Number of fatalities in 1995	Number of fatalities per fire occurrence in 1995
Public	7.338	18	$2,45\ 10^{-3}$
Dwellings/office	60.312	209	$3,46\ 10^{-3}$
Industrial buildings	6.210	6	$0,97\ 10^{-3}$
Warehouse	8.318	3	$0,36\ 10^{-3}$

Table 3.5: Number of fatalities and fire per activity in 1995

Therefore the industrial risk of fire fatality in buildings is $(236 / 55) \cdot 10^{-6} = 4,3 \cdot 10^{-6}$ per year. The total individual fire risk is $(715 / 55) \cdot 10^{-6} = 13,0 \cdot 10^{-6}$ per year.

Statistics exist for different years. Figure 3.5 gives the repartition of fatalities per activity in 1986 and 1995. Without the car fires that increased with a ratio 12 in 10 years, the distribution and the number of fires did not change in 10 years.
Figure 3.6 which shows the number of fire and of injured people occurring in dwellings and office buildings in 1975, 1984 and 1995, confirms this conclusion. It appears that the number of injured people per fire: 0.04 is quite constant.

Figure 3.7 coming from the Fire Brigade of PARIS review 'allo 18', shows that the number of fires in Paris has not changed in 4 years.

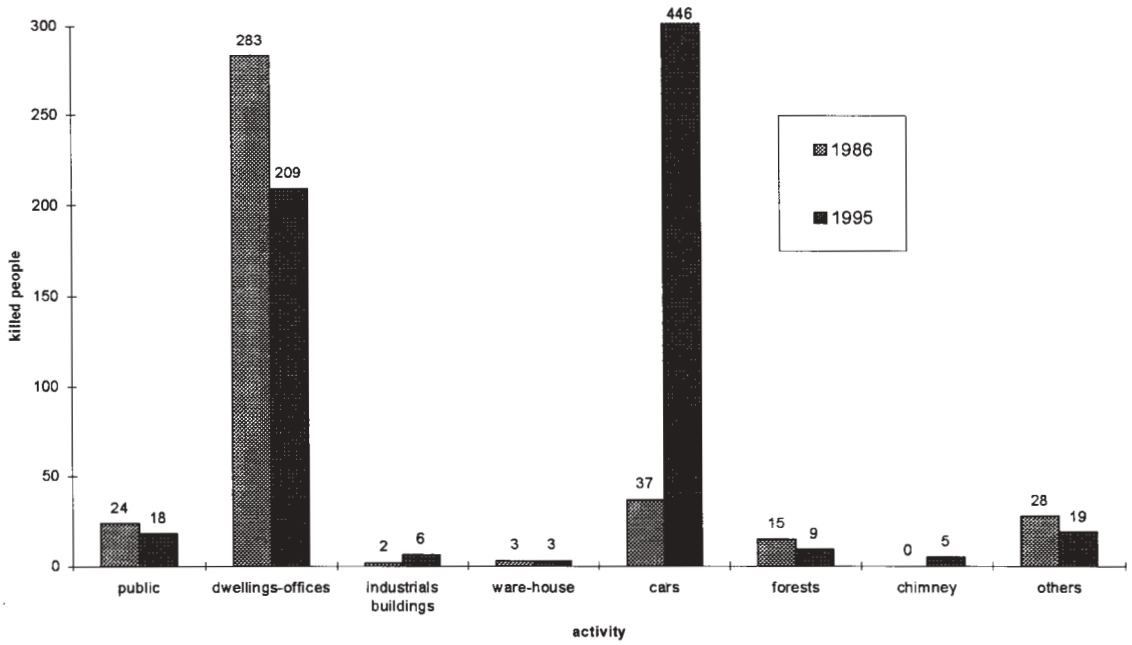


Figure 3.5: Fatalities per activity in 1986 and in 1995

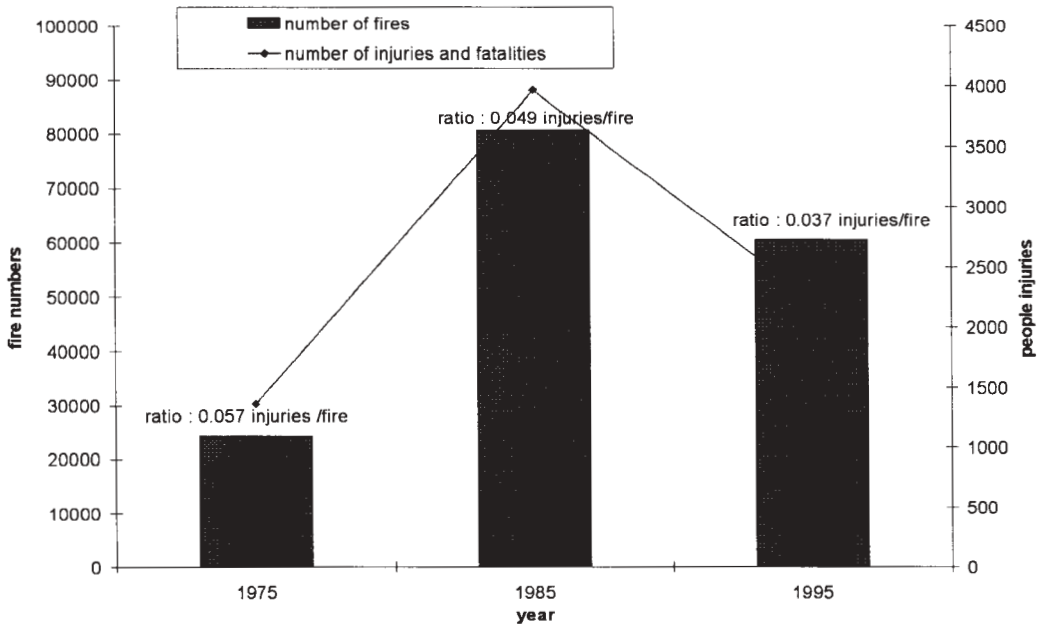


Figure 3.6: Evolution of injured people in dwellings and office buildings in 1975, 1985 and 1995

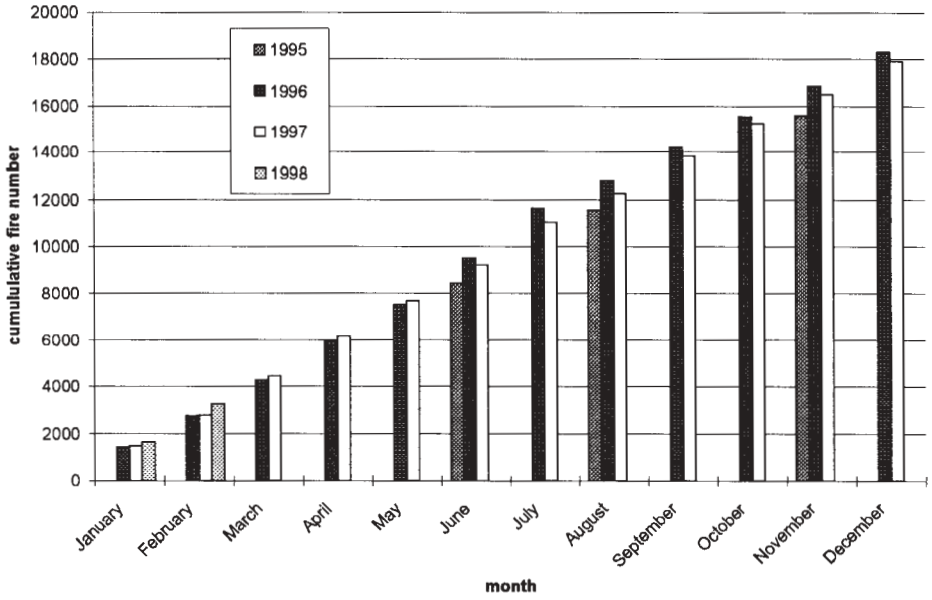


Figure 3.7: Number of fires in Paris in 1995, 1996, 1997 and 1998

3.2 BRITISH DATABASE

In the paper "The Estimation of the Hazard in Different Occupancies", [14] Rutstein describes a study of fire hazard using information derived from fire brigade statistics and fire loss statistics. This data is partially included in annex B of [3].

3.2.1 FIRE HAZARD FOR DIFFERENT OCCUPANCIES

	Probability of fire per year [fire / year]	Average amount of fire damage [m^2]	Direct loss per m^2 of fire damage [£]	Fire hazard [£ / year]
All industry	$0{,}0017 \cdot A^{0,53}$	$2{,}25 \cdot A^{0,45}$	140	$0{,}54 \cdot A^{0,98}$
Storage	$0{,}00067 \cdot A^{0,5}$	$3{,}5 \cdot A^{0,52}$	120	$0{,}28 \cdot A^{1,02}$
Shops	$0{,}000066 \cdot A^{1,0}$	$0{,}95 \cdot A^{0,50}$	160	$0{,}01 \cdot A^{1,5}$
Offices	$0{,}000059 \cdot A^{0,9}$	15,0	150	$0{,}13 \cdot A^{0,9}$
Hotels	$0{,}00008 \cdot A^{1,0}$	$5{,}4 \cdot A^{0,22}$	130	$0{,}056 \cdot A^{1,22}$
Hospitals	$0{,}0007 \cdot A^{0,75}$	5,0	160	$0{,}56 \cdot A^{0,75}$
Pubs, restaurants	$0{,}00007 \cdot A^{1,0}$	$7{,}6 \cdot A^{0,20}$	100	$0{,}053 \cdot A^{1,2}$
Schools	$0{,}0002 \cdot A^{0,75}$	$2{,}8 \cdot A^{0,37}$	110	$0{,}062 \cdot A^{1,12}$

Table 3.6: Fire hazard in different occupancies [14] as a function of total floor space A of the building

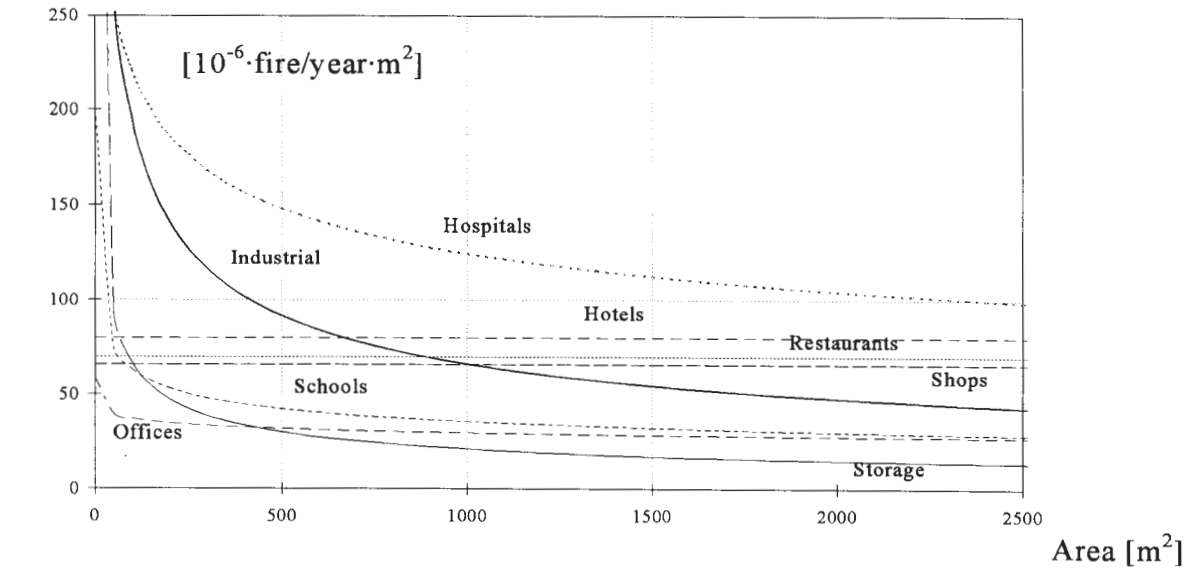


Figure 3.8: Probability of fire per year and m^2

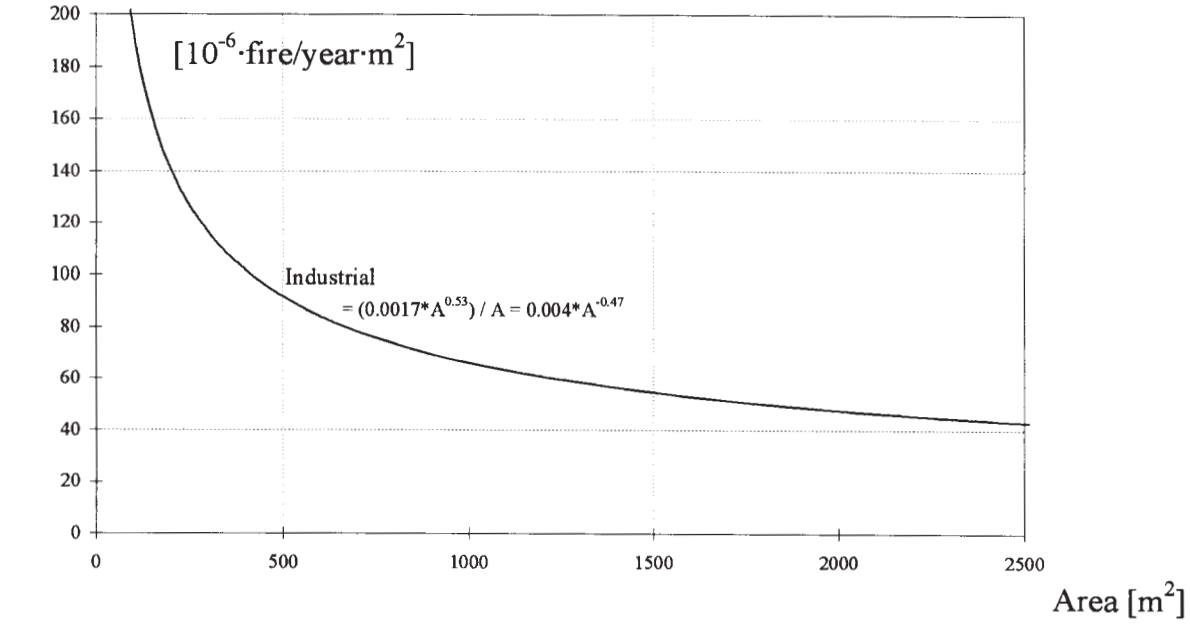


Figure 3.9: Probability of fire per year and m^2 as a function of total floor space A of the industrial building

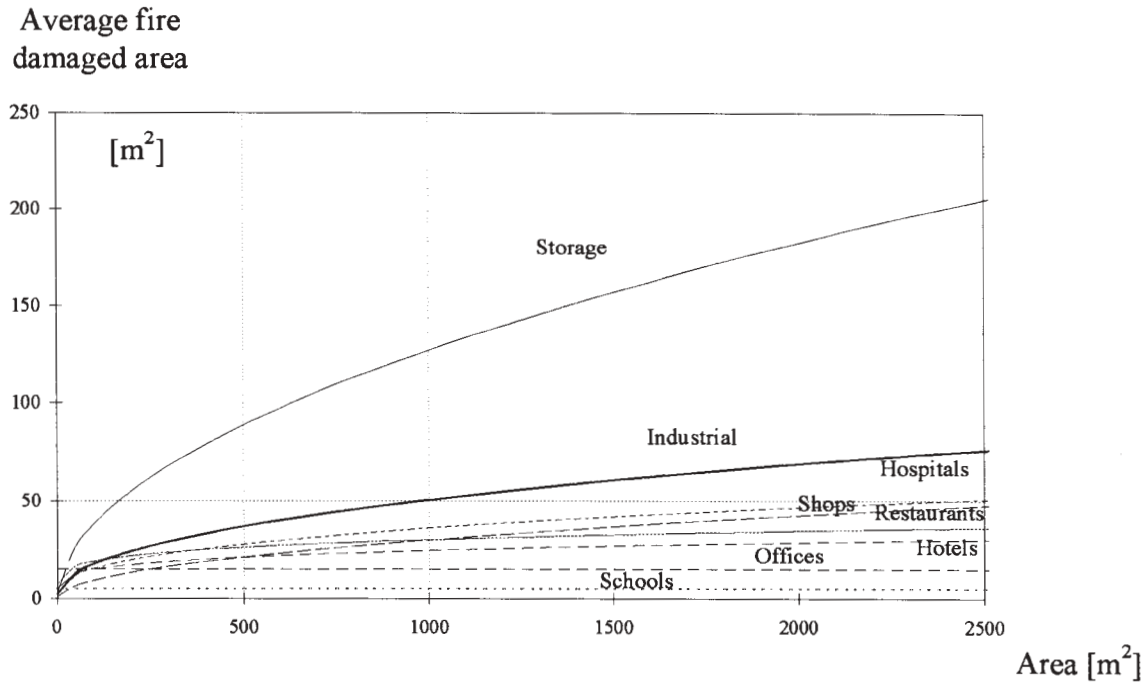


Figure 3.10: Average amount of fire damaged area [m²] as a function of total floor space A of the building

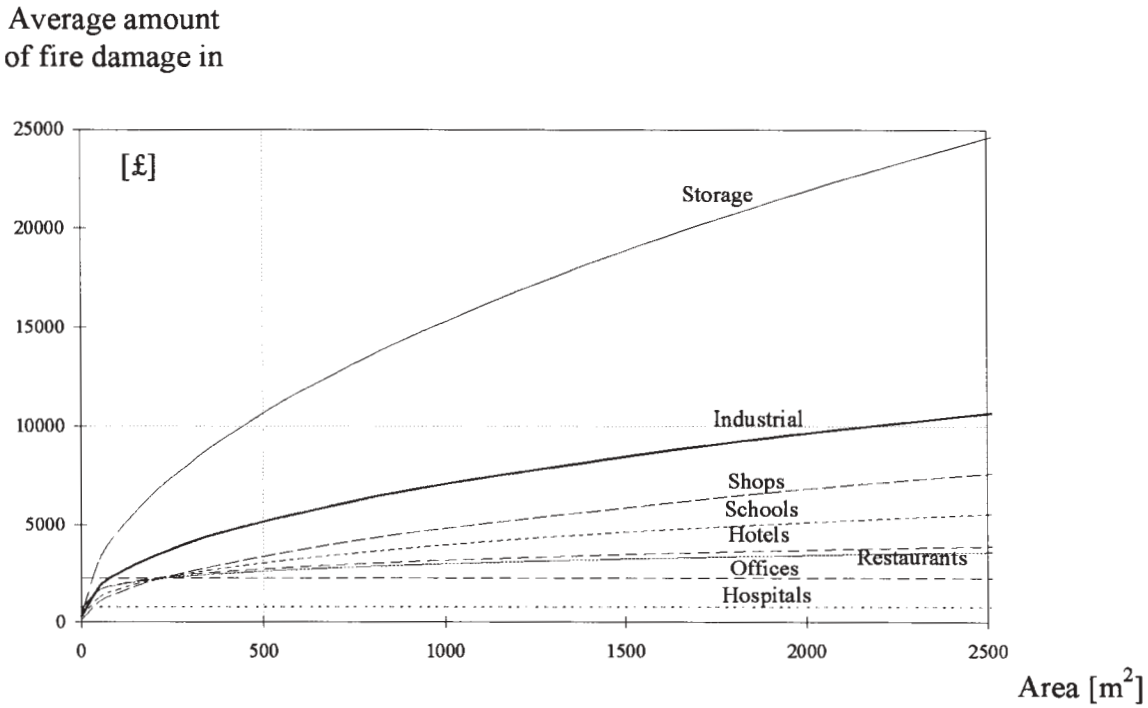


Figure 3.11: Average amount of financial fire damage as a function of total floor space A of the building

3.2.2 COMPARISON OF RELATIVE FIRE DAMAGE : UK - CH

From the Rutstein data [14] (see Table 3.6) the relative damage in function of the area at risk is plotted in Figure 3.12 for industrial buildings. The relative damage decreases with increasing floor space of the building.

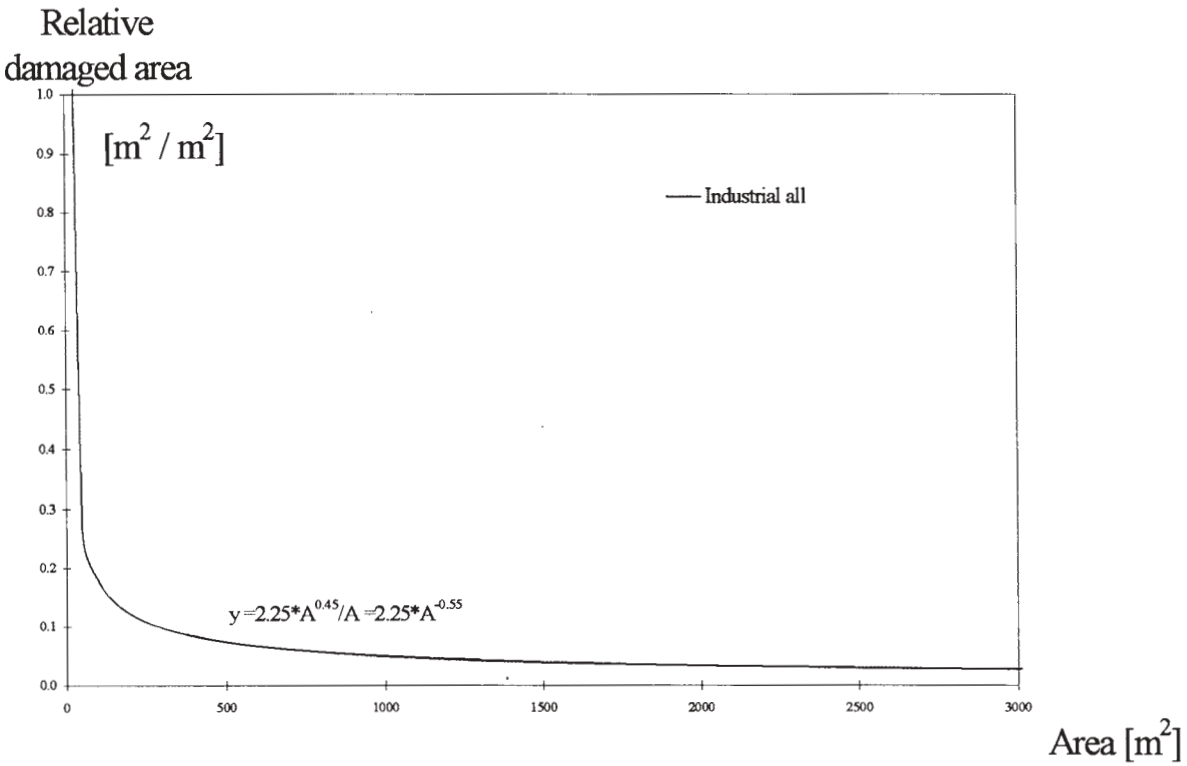


Figure 3.12: Relative loss (damaged area / total floor space of building) in UK as a function of the total floor space A of the building

From the major fire losses in the Canton of Berne (loss > 10^6 CHF) given in chapter 2.1 a similar trend of decreasing loss with increasing value at risk can be seen. However, the relation is different, because in contrast to the Rutstein data only the small selective group of major losses is taken into account leading to a much higher relative loss.

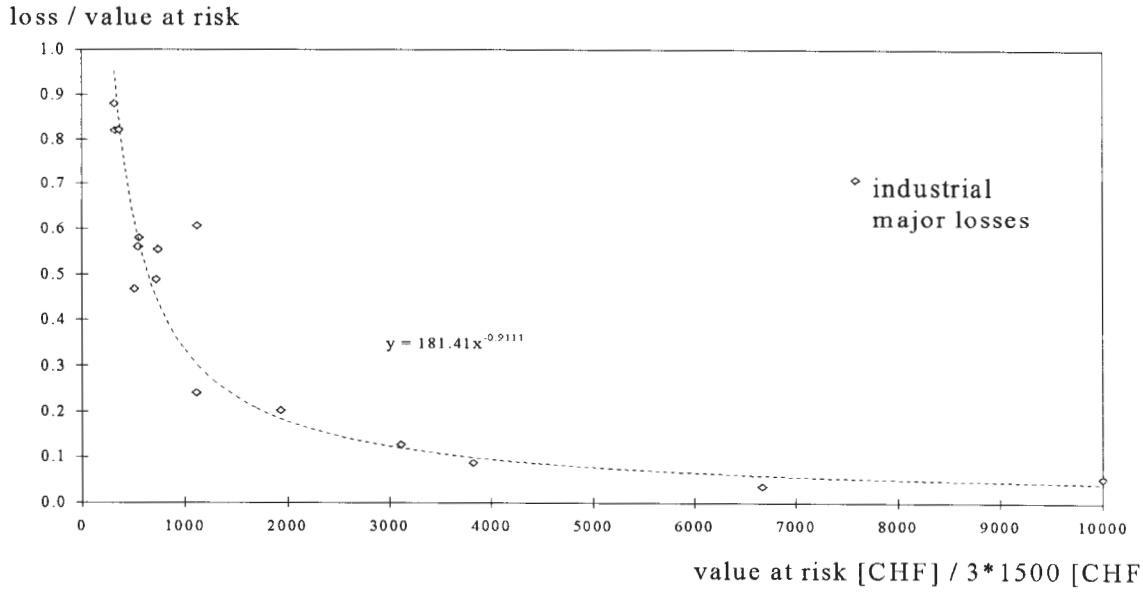


Figure 3.13: Relative loss (loss on building / value of building) as a function of the value at risk (Assumption: building value = 1500 CHF/m^2, value of the contents twice the building value) for major losses (> 10^6 CHF) for all major losses > 10^6 CHF in industrial buildings in the Canton of Berne (1986-95)

Taking all industrial fires in Berne from 1988-97 (n_{tot} = 1774 fires). The relation loss as a function to the value at risk is given in Figure 3.14.

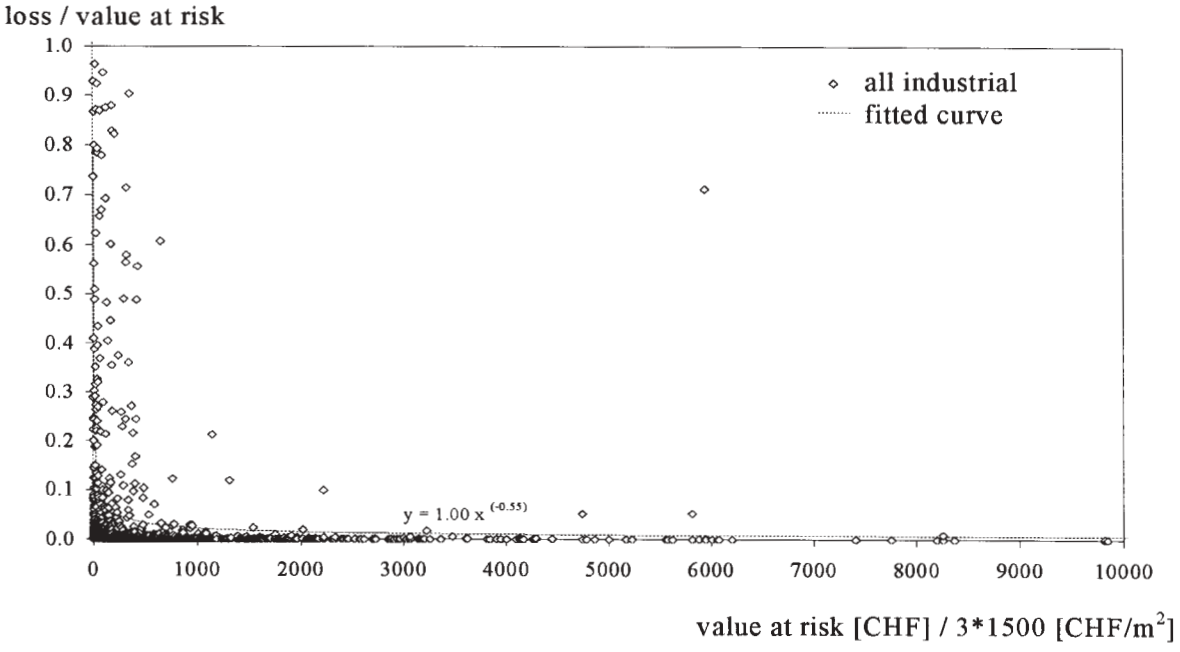


Figure 3.14: Relative loss (loss on building / value of building) as a function of the value at risk (Assumption: Building value = 1500 CHF/m^2, value of the contents twice the building value) for all losses in industrial buildings in the Canton of Berne (1988-97)

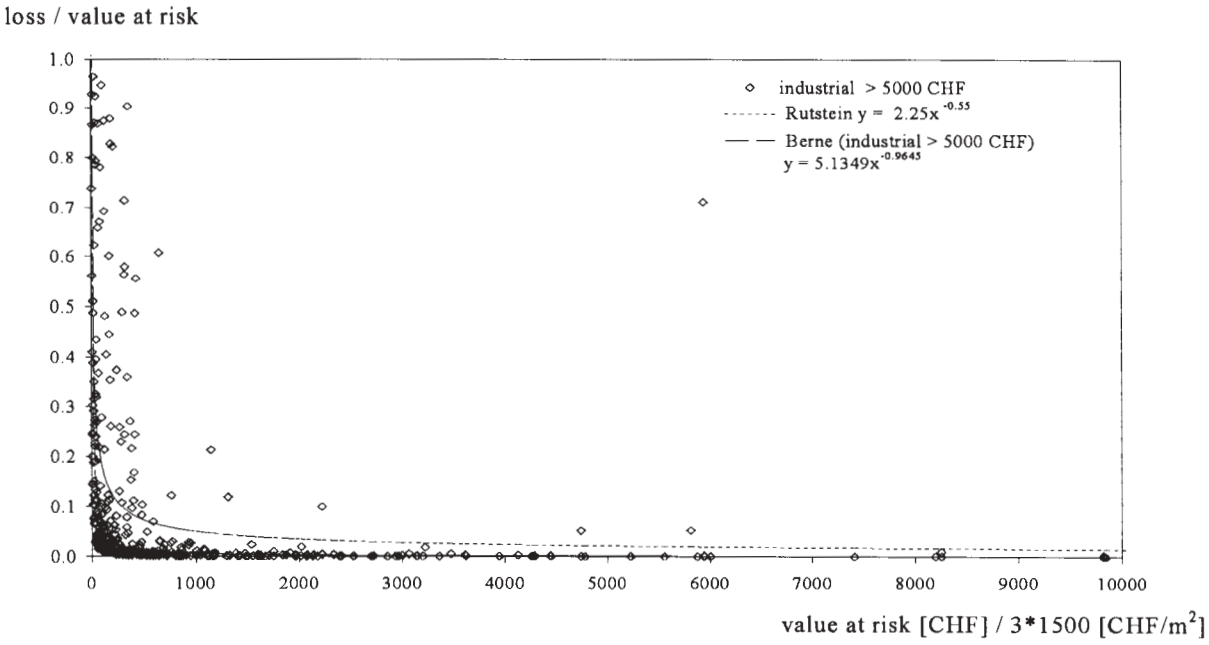


Figure 3.15: Relative loss (loss on building / value of building) as a function of the value at risk (Assumption: Building value = 1500 CHF/m^2, value of the content two times the building value) for all losses in industrial buildings (> 5000 CHF) in the canton of Berne (1988-97)

It is evident from Figures 3.12 to 3.15 that the loss statistics are very dependent on the sample characteristics. If only fires larger than a minimum size are considered the relative loss will increase.

3.2.3 COMPARISON OF THE AMOUNT OF FIRE DAMAGE

According to the data of Rutstein [14] the amount of fire damage increases under-proportional to the increase of the total floor space of a building.

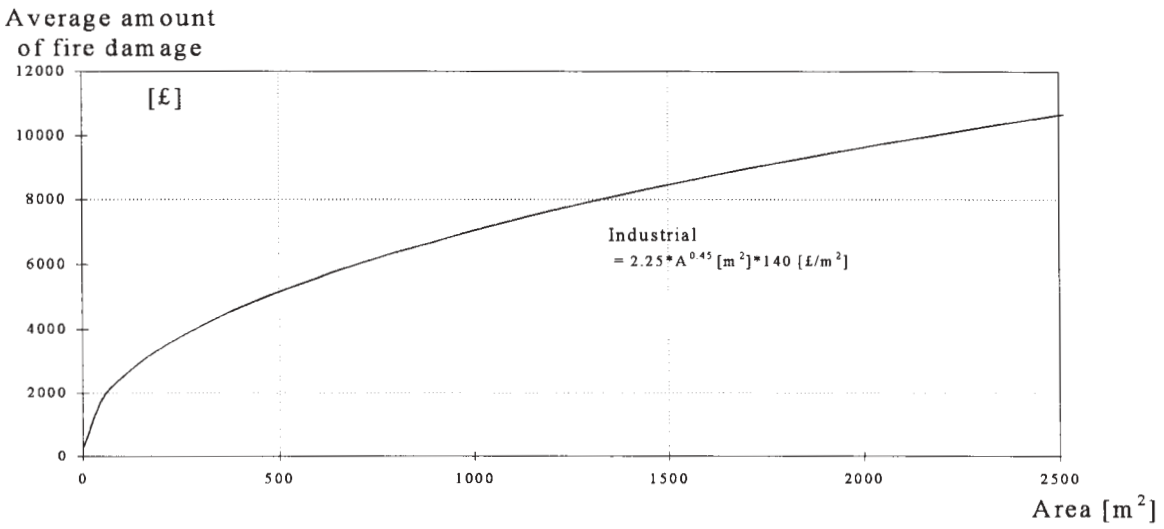


Figure 3.16: Average amount of fire damaged area multiplied with the direct loss per m^2 of fire damage for industrial buildings [14] in UK

Again the same trend can be found from the major fire losses (> 10^6 CHF) in Berne, but as only major fire losses (15 of all the 1538 industrial fires reported in that period e.g. 1%) are in this statistical group the absolute values are much higher

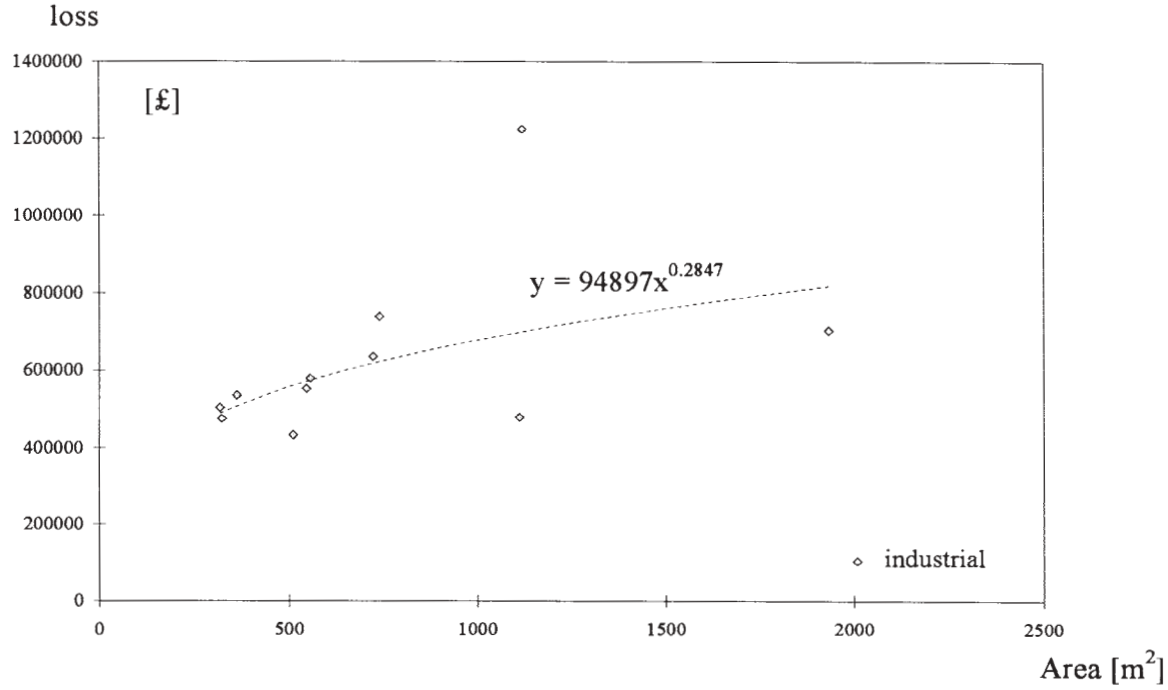


Figure 3.17: Amount of fire damage (loss on building) compared to the value at risk for major losses (each loss > 10^6 CHF) in the Canton of Berne (1986-95) for an assumed value at risk of CHF 4500/m²

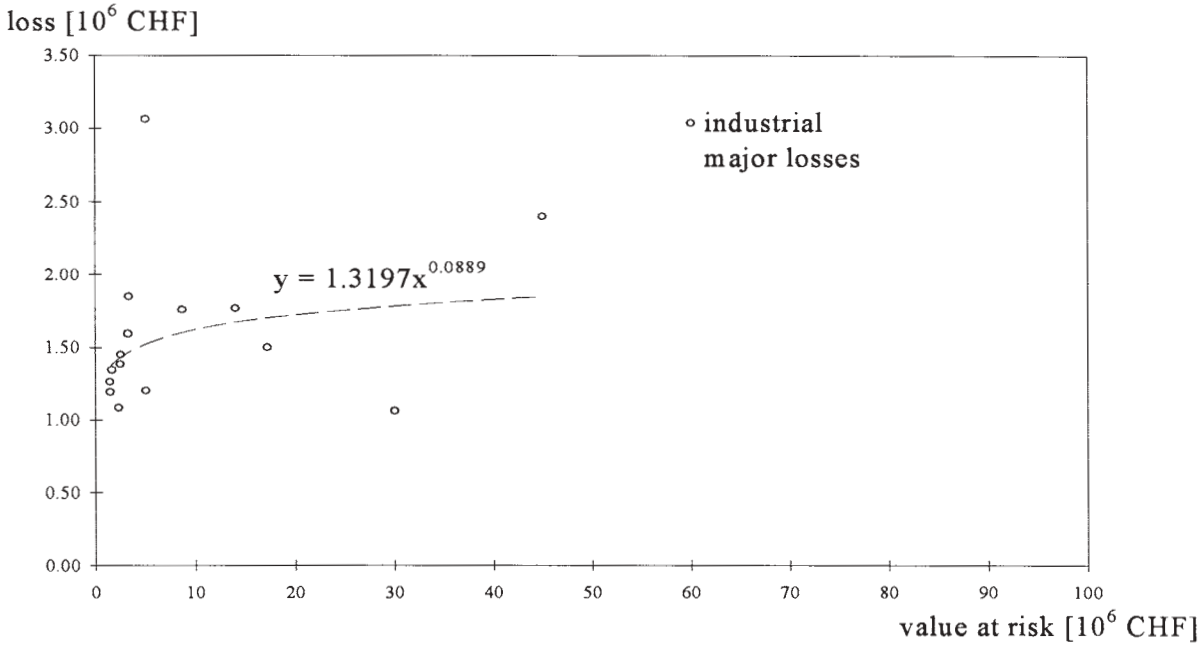


Figure 3.18: Amount of fire damage (loss on building) compared to the value at risk for major losses (each loss > 10^6 CHF) in the Canton of Berne (1986-95)

For all losses in industrial buildings from 1988-1997 in Berne Figure 3.16 gives the amount of fire loss to the building compared to the building value. Again the influence of the sample size is clearly visible.

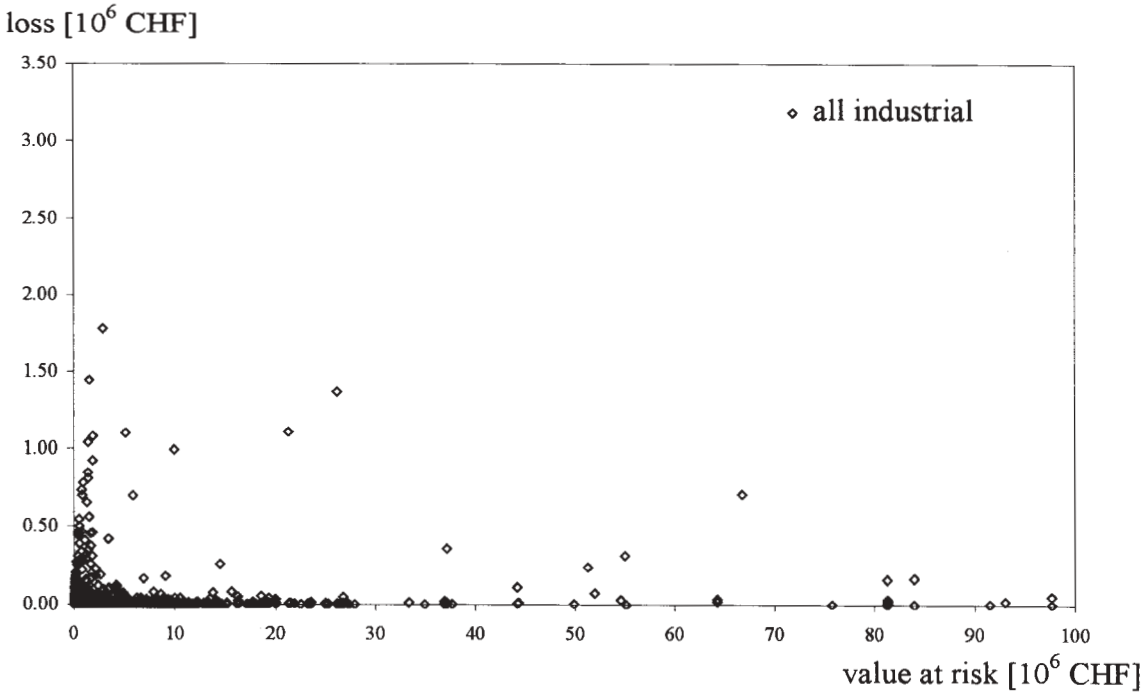


Figure 3.19: Amount of fire damage (loss on building) compared to the value at risk for all losses in the Canton of Berne (1988-97)

3.3 DUTCH DATABASE

Parallel to the French survey (see chapter 3.1) a survey on industrial fires in the Netherlands was performed for the period 1.10.83 to 31.1.85 for 29 fires with a loss larger than 100.000 NLG (approx. 50.000 ECU). Each fire was visited by a team of TNO experts. A summary of the Dutch data can be found on the following pages. This data will be made available by TNO for NFSC on diskette.

I General Information

Serial number	Date of fire	Activity	
		Utilisation [1]	Type of industry
12	18-10-'83	commercial	food and allied products industry
2	24-10-'83	storage	wood working and furniture industry
3	27-10-'83	manufacture	metallic products industry
4	07-11-'83	storage	means of transport industry
5	21-11-'83	storage	engineering industry
6	08-01-'84	storage	food and allied products industry
7	19-01-'84	assembling	rubber, synthetic material working industry
8	02-02-'84	empty	Ship-building industry
9	06-03-'84	manufacture	wood working and furniture industry
10	13-03-'84	storage	almost empty
11	15-03-'84	storage	food and allied products industry
12	11-04-'84	manufacture	food and allied products industry
13	02-05-'84	storage	chemical industry
14	25-04-'84	assembling	building materials, glass, and earthenware industry
15	14-05-'84	storage	rubber, synthetic material working industry
16	19-05-'84	storage	wood working and furniture industry
17	24-06-'84	assembling	graphic industry
18	01-07-'84	storage	rubber, synthetic material working industry
19	10-07-'84	storage	ship building industry
20	30-07-'84	manufacture	metallic products industry
21	07-08-'84	manufacture	rubber, synthetic material working industry
22	13-08-'84	commercial	wood working and furniture industry
23	03-09-'84	storage	wood working and furniture industry
24	20-09-'84	empty	empty
25	23-10-'84	manufacture	building materials, glass and earthen ware industry
26	28-12-'84	storage	food and allied products industry
27	07-11-'84	storage	means of transport industry
28	27-11-'84	storage	remaining
29	30-01-'85	storage	remaining

[1] based on utilisation of room of fire initiation

II Building

Serial number	Construction period	Classification according to material used for load bearing structure		Classification according to CEA	Thermal inertia construction	Number of stories	Area of the building			Value at risk of the building [* DFL 1000]		
		Main load bearing structure	Roof				Building on fire [m^2]	Firm on fire [m^2]	Room of fire initiation [m^2]	Building on fire	Firm on fire	Room of fire initiation
1	after 1960	Steel	Steel	3 2 1 2 2	Medium	1(2)	10500	10500	375	13.000	13.000	465[1)]
2	after 1960	Steel	Steel	3 3 1 4 1	Low	1(2)	23100	13100	2800	9.304	9.304	2.000
3	after 1960	Wood	Wood	2 1 1 1 1	Low	1	7700	2200	2200	3.470	1.008	1.008
4	before 1960	Masonry	Wood	3 2 2 3 1	Low	2	540	380	380	50	50	50
5	before 1960	Steel	Steel	3 4 1 4 2	Low	1	7300	7300	610	9.500	9.500	200
6	after 1960	Steel	Steel	3 2 1 2 1	Medium	1	800	800	400	5.600	5.600	825[3)]
7	after 1960	Steel	Steel	3 2 1 2 1	Medium	1(2)	480	160	160	950	300	300
8	before 1960	Wood	Wood	4 3 2 3 1	Low	2	2160	2160	350	1.616	1.616	110
9	after 1960	Wood	Wood	2 3 1 4 2	Low	1(2)	1335	770	300	2.000	1.150[1)]	450[1)]
10	after 1960	Steel	Steel	3 2 2 4 1	Medium	2	2400	2400	900	2.753	2.753	1.377
11	before 1960	Masonry	Wood	3 3 1 4 1	Medium	1	4265	4265	2680	2.000	2.000	1.260[1)]
12	before 1960	Steel	Steel	3 1 2 4 1	Medium	2	1500	1500	360	1.480	1.480	800
13	after 1960	Steel	Steel	3 2 1 2 1	Medium	1(2)	4950	2615	2615	5.700	2.700	2.700
14	after 1960	Steel	Steel	3 2 1 2 1	Medium	1(2)	1000	1000	1000	1.000	1.000	1.000
15	before 1960	Steel	Steel	3 2 1 2 1	Medium	1	4160	2080	1040	3.000	1.500[1)]	750[1)]
16	after 1960	Wood	Wood	4 3 1 3 1	Low	1	2875	2875	2875	945	945	945
17(4)	unknown	Masonry	Wood	1 2 1 4 1	Medium	1(3)	285	285	75	367	367	97[1)]
18	after 1960	Masonry	Wood	1 2 1 4 1	Medium	1	900	900	750	445	445	370[1)]
19	before 1960	Steel	Steel	3 3 1 1 1	Low	1	3530	3530	1296	2.500	2.500	900[1)]
20	before 1960	Concrete	Wood	1 1 1 4 1	Medium	1	2060	2060	1800	1.900	1.900	1.300
21	after 1960	Steel	Steel	3 3 1 4 2	Medium	1	2400	600	600	780	195[1)]	195[1)]
22	after 1960	Steel	Steel	3 2 1 4 1	Medium	1	4110	510	510	unknown	unknown	unknown
23	after 1960	Steel	Steel	3 2 2 4 1	Medium	2	1522	1522	120	1.588	1.588	125[1)]
24	after 1960	Concrete	Concrete	3 2 1 4 1	Medium	1	2565	2565	300	1.100	1.100	290
25	before 1960	Steel	Steel	4 3 2 4 1	Medium	2(3)	2000	2000	600	667	669	207[1)]
26	before 1960	Steel	Steel	3 2 1 4 2	Medium	1	3900	3900	480	unknown	unknown	unknown
27	after 1960	Steel	Steel	3 2 1 4 2	Medium	1	5940	450	450	3.550[1)]	268	268
28	after 1960	Steel	Steel	3 3 1 4 2	Medium	1	618	618	165	1.400	1.400	375[1)]
29	before 1960	Wood	Wood	2 2 1 4 2	Medium	1	560	560	360	350	350	225[1)]

(1) = proportional to surface
(2) - empty house was declared unfit for habitation
(3) - derived from direct loss and general situation
(4) - dwelling above publishing fire kept out on study

III Contents

Serial number	Fire load [kg/m^2]	Fire hazard of contents	Value of contents at risk [* DFL 1000]		
			Building on fire	Firm on fire	Room of fire initiation
1	40	low	16.000	16.000	25[1)]
2	120	high	2.880	2.880	615
3	30	low	11.620	3.041	3.041
4	30	low	23	23	23
5	90	high	8.160	8.160	1.550
6	45	high	1.650	1.650	150
7	60	high	970[1)]	323	323
8	30	low	unknown	unknown	1[2)]
9	60	high	305	237	108
10	15	high	200	200	200
11	20	low	40[3)]	40[3)]	25
12	45	low	2.184	2.184	1.483
13	60	low	9.945	8.500	8.500
14	15	high	1.000	1.000	1.000
15	75	high	860[1)]	575	288[3)]
16	230	high	1.107[1)]	1.107[1)]	1.107[1)]
17	120	low	689	689	180
18	120	high	580	580	529
19	90	low	2.502	2.502	450[1)]
20	45	low	5.450	5.450	4.730[1)]
21	15	high	3.919	1.919	1.919
22	25	low	1.015	150	150
23	90	low	484	484	38
24	25	low	3[2)]	3[2)]	3[2)]
25	45	low	108	108	33[3)]
26	90	high	unknown	unknown	unknown
27	60	high	unknown	614	614
28	45	low	200	200	100
29	60	low	1.300	1.300	835[1)]

[1)] derived from direct loss and general situation
[2)] empty
[3)] proportional to surface

IV Fire

Serial number	Time of fire outbreak	Estimated time of fire duration before alarm [min]	Exact time alarm [MET]	Arrival of fire brigade after alarm [min]	State of fire at arrival fire brigade	Entry of the building by fire brigade	Time of fire under control after alarm [min]
1	not during working hours	20	00.10	4	medium	yes	69
2	during working hours	15	13.47	9	large	no: due to behaviour of construction	137
3	not during working hours	15	04.15	8	large	yes	139
4	during working hours	15	09.35	6	small	yes	15
53	during working hours	2	14.51	5	medium	yes	125
6	during working hours	18	04.28	2	medium	yes	34
7	not during working hours	20	22.01	7	medium	no: due to behaviour of construction	77
8	not during working hours	60	20.00	7	large	yes	54
9	not during working hours	60	03.20	3	large	yes	85
10	not during working hours	15	03.15	2	medium	no: due to behaviour of construction	120
11	not during working hours	15	01.30	8	medium	yes	45
12	not during working hours	120	07.07	9	medium	yes	54
13	not during working hours	unknown	00.00	6	large	no: due to heat or smoke	172
14	not during working hours	unknown	23.05	7	small	yes	25
15	not during working hours	17	17.27	5	medium	yes	25
16	not during working hours	30	17.13	2	large	no: due to behaviour of construction	67
17	not during working hours	3	14.06	2	small	yes	4
18	not during working hours	13	16.08	8	medium	yes	94
19	not during working hours	33	19.33	7	small	yes	60
20	not during working hours	40	23.31	3	large	no: due to behaviour of construction	58
21	not during working hours	30	10.07	15	medium	no: due to behaviour of construction	40
22	not during working hours	20	23.41	14	large	yes	66
23	not during working hours	90	01.36	10	medium	yes	204
24	during working hours	10	15.50	2	medium	yes	83
25	during working hours	90	13.30	5	medium	yes	48
26	during working hours	15	06.09	9	large	yes	72
27	not during working hours	120	01.16	2	medium	yes	120
28	not during working hours	unknown	05.24	7	medium	yes	70
29	not during working hours	20	01.40	6	medium	yes	174

V Fire safety devices

Serial number	Automatic detection		Automatic extinguishing		Compartmentation		
	Present	Estimated loss reduction	Present	Estimated loss reduction	Present	Effect	Reason for being effective
1	no	obvious	no	most essential	yes	effective	in combination with action of fire brigade
2	no	obvious	no	most essential	yes	not effective	due to openings/penetrations
3	no	obvious	no	most essential	yes	not effective	due to deformation
4	no	some	no	obvious	yes	not effective	due to insufficient fire resistance
5	no	very limited	no	some	yes	effective	in combination with action fire brigade
6	no	obvious	no	obvious	yes	effective	in combination with action fire brigade
7	no	obvious	no	most essential	yes	effective	in combination with action fire brigade
8	no	most essential	no	most essential	no		
9	no	obvious	no	most essential	yes	not effective	due to openings/penetrations
10	no	obvious	no	most essential	yes	not effective	due to openings/penetrations
11	no	most essential	no	most essential	yes	effective	in combination with action fire brigade
12	no	most essential	no	obvious	yes	effective	because of architectural construction
13	no	obvious	no	most essential	yes	not effective	due to openings/penetrations
14	no	some	no	some	no		
15	no	obvious	no	most essential	yes	effective	in combination with action fire brigade
16	no	obvious	no	some	no		
17	no	very limited	no	very limited	yes	effective	because of architectural construction
18	no	obvious	no	most essential	yes	effective	in combination with action fire brigade
19	no	obvious	no	some	yes	effective	in combination with action fire brigade
20	no	obvious	no	most essential	no		
21	no	obvious	no	obvious	yes	not effective	due to influence not structural connections
22	no	obvious	no	most essential	yes	effective	because of architectural construction
23	no	most essential	no	most essential	no		
24	no	some	no	most essential	yes	effective	in combination with action fire brigade
25	no	obvious	no	obvious	yes	not effective	due to openings/penetrations
26	no	obvious	no	most essential	yes	not effective	due to openings/penetrations
27	no	most essential	no	some	yes	not effective	due to openings/penetrations
28	no	obvious	no	most essential	yes	not effective	due to openings/penetrations
29	no	some	no	most essential	no		

VI Consequences of fire

Serial number	Area exposed to fire	Additional area exposed to smoke	Structural damage	Casualties		Monetary losses [* DFL 1000]						
				injured	deaths	Direct. building		Direct, contents		Indirect		Direct, adjacent building
						Building on fire	Firm on fire	Building on fire	Firm on fire	Building on fire	Firm on fire	
1	403	5000	No	0	0	756	756	522	522	24	24	---
2	12900	---	Major	0	0	7.848	7.844	2.780	2.780	unknown	unknown	0
3	5800	1100	Major	0	0	2.611	1.008	10.808	2.994	1.552	1.300(1)	---
4	290	180	Major	1	0	50	50	11	11	0	0	---
5	378	4000	No	0	0	200	200	1.100	1.100	150	150	---
6	400	0	Major	0	0	816	816	148	148	2.811	2.811	---
7	192	80	Major	0	0	492	450	265(2)	255	59	24	10
8	175	175	Minor	0	0	66	66	1(3)	1(3)	0	0	0
9	530	600	Major	0	0	850	unknown	143	128	125	1	36
10	2400	---	Major	0	0	2.753	2.753	200	200	310	310	---
11	400	500	No	0	0	287	287	20	20	25	25	80
12	380	360	Minor	0	0	301	301	713	713	unknown	unknown	---
13	3950	1000	Major	1(4)	0	3.300	2.300	10.150	8.500	3.050	3.050	---
14	200	800	No	0	0	250	250	450	450	450	450	---
15	200	1350	No	0	0	347	347	387	387	60	60	---
16	2875	---	Major	2(4)	0	945	945	1.106	1.106	520	520	40
17	5	230	No	0	0	19	19	16	16	20	20	0
18	752	70	Major	0	0	403	403	529	529	11	11	0
19	360	750	No	0	0	245	245	379	unknown	unknown	---	---
20	1805	---	Major	0	0	1.300	1.300	4.730	4.730	1.060	1.060	0
21	900	900	Minor	0	0	137	137	2.099	1.919	4	4	---
22	1360	850	Major	0	0	unknown	unknown	277	150	unknown	---	24
23	1325	10	Major	0	0	1.286	1.286	484	484	200(3)	200(3)	---
24	300	400	Minor	0	0	290	290	3	3	unknown	---	---
25	300	400	Minor	0	0	211	211	24	24	67	67	---
26	2670	500	Major	0	0	2.400	2.400	9.800	9.800	3.500	3.500	---
27	450	150	Minor	0	0	unknown	249	unknown	429	unknown	200	---
28	350	250	Major	0	0	600	600	200	200	24	24	---
29	360	200	Major	0	0	263	263	1.300	1.300	1.300	27	

(1) Company not continued because of retirement owner/user (2) Derived from direct loss and general situation (3) Empty (4) Member(s) of fire brigade

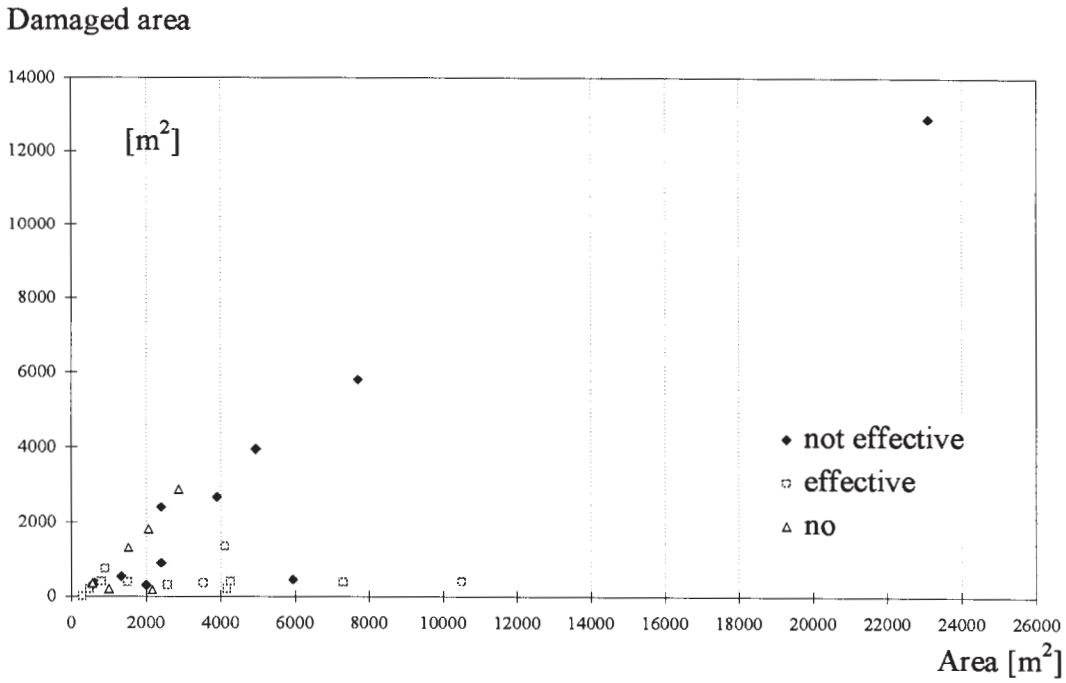


Figure 3.20: Damaged area [m^2] as a function of total floor space A of the building and the effect of the compartmentation for the Dutch database (1983 - 85)

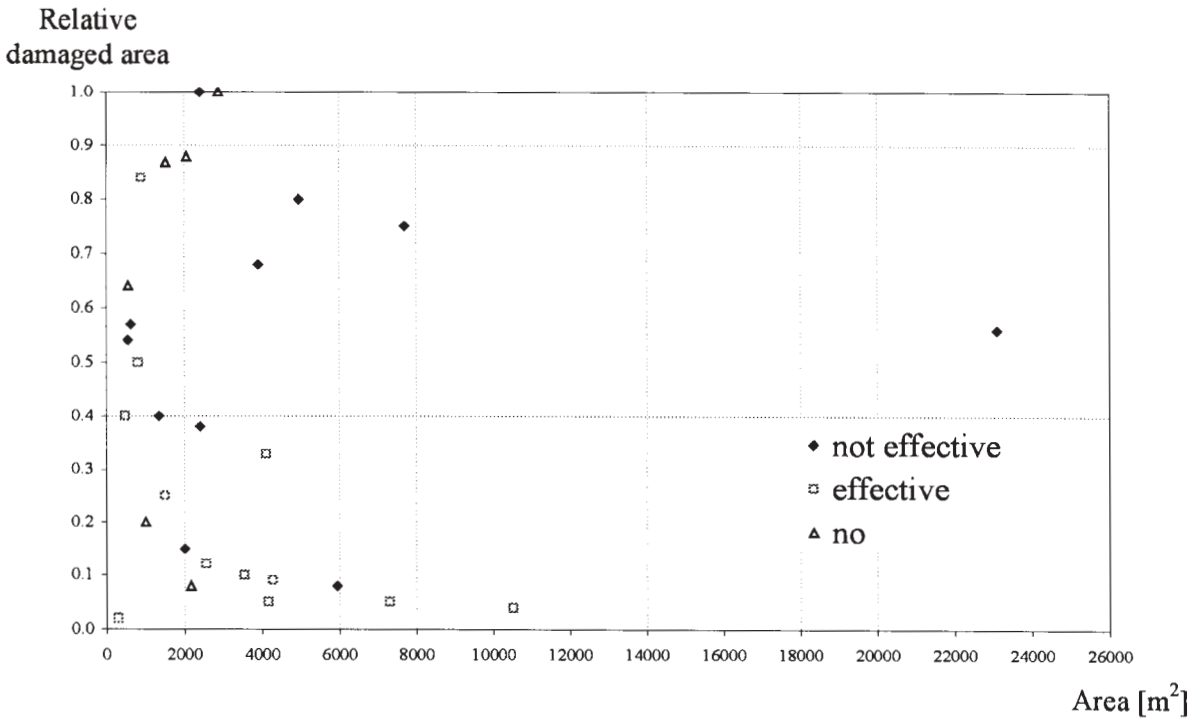


Figure 3.21: Relative damaged area [m^2] as a function of total floor space A of the building for the Dutch database (1983 - 85)

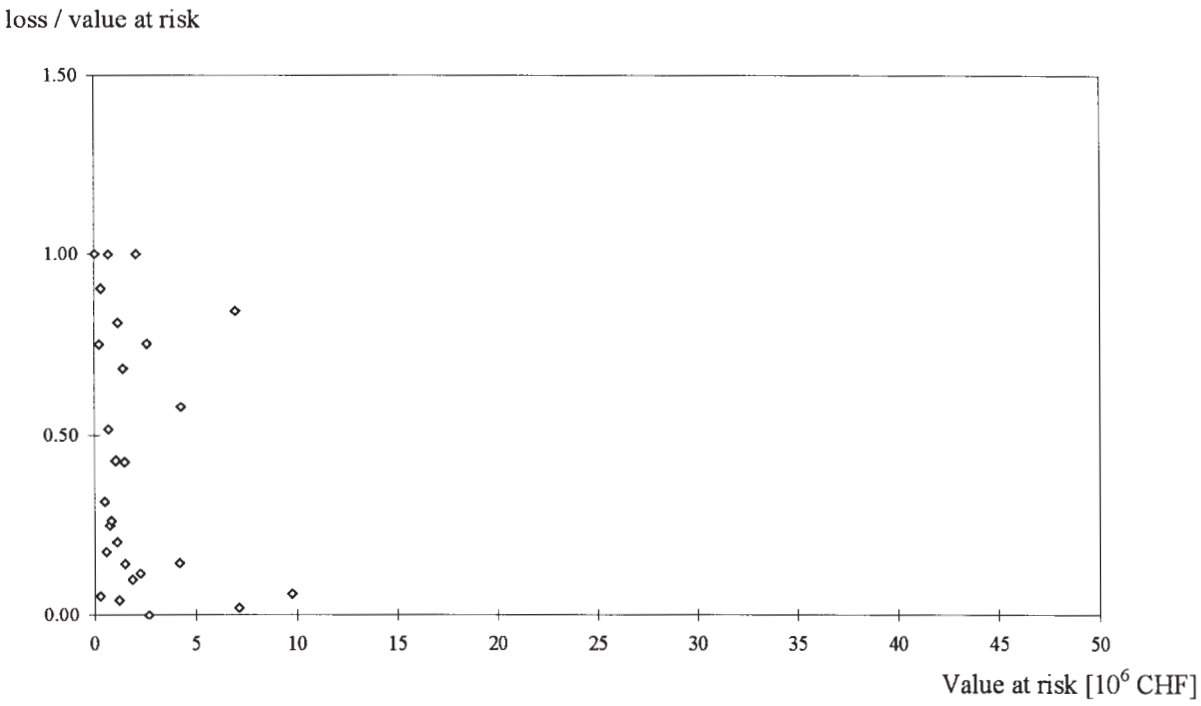


Figure 3.22: Relative loss (loss on building / value of building) compared to the value at risk for industrial buildings of the Dutch database (1983 - 85)

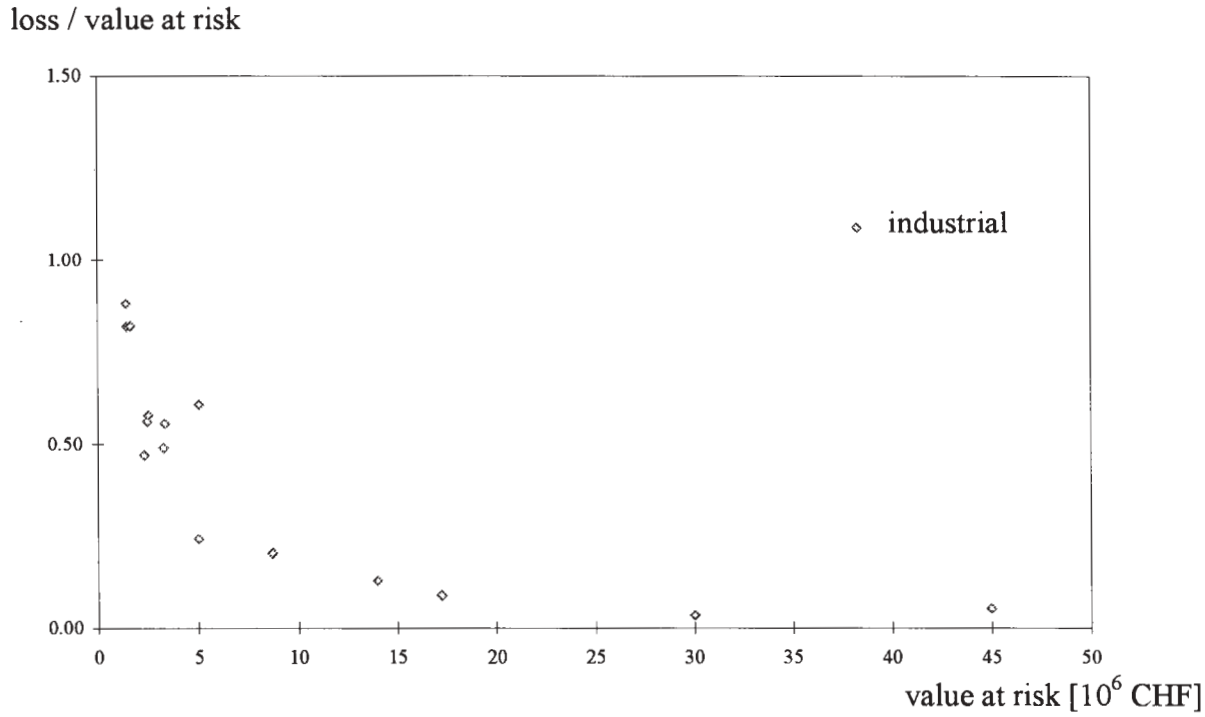


Figure 3.23: Relative loss (loss on building / value of building) compared to the value at risk for industrial buildings of the Swiss database (1986-95 all losses > 10^6 CHF)

3.4 FINISH DATABASE [13]

The results are based on combining the information in the national fire statistics database ONTIKA of the Ministry of Interior and other relevant national statistical databases for the year 1995. This database is collected by fire brigades. Consequently, fires not reported to the fire brigade are not included in the database. Due to the database system it has been estimated that up to 25% of the fires have not been reported at all.

The total number of building fires entered into the database was 3.251. About 25% of those were in farm buildings, forestry or traffic, where no reliable building data is available. In addition, about 20% of the cases reported were only partial, preventing the use of data in parts of the study. The analysis is thus based on 2.109 fires. The total number of building in the survey was 1.150.494 out of which 1.035.580 (90%) were residential buildings.

Occupancy class	Number of buildings	frequency per year and building $[10^{-3}]$	frequency per year and floor area $[10^{-6}] / (m^2 \cdot year)$
Residential building	1.043.296	1,6	7,1
Shop, accommodation and restaurant building	33.348	4,6	8,5
Institutional buildings, (e.g. hospitals)	6.018	13	9,5
Office building	10.300	2,5	1,7
Assembly building	10.394	2,9	4,6
Educational building	8.984	5,1	3,1
Industrial building	29.612	14	11,0
Warehouse	16.036	6,2	8,1
Total	1.150.494	2,1	7,2

Table 3.6: Frequency of fire starts per year for different occupancy classes

The probability of fire starts per unit floor area depends on the size of the building. For buildings larger than 90 m^2 the dependency can be expressed as

$p_{fire} = 3{,}2 \cdot 10^{-5} \cdot A^{-0{,}28}$

Units: $P_{fire} = [1 / (m^2 \cdot year)]$

$A = [m^2]$

Note: for a comparison with the UK data see Table 3.5.

The probability of fire starts in this equation is based on the complete set of reported data.

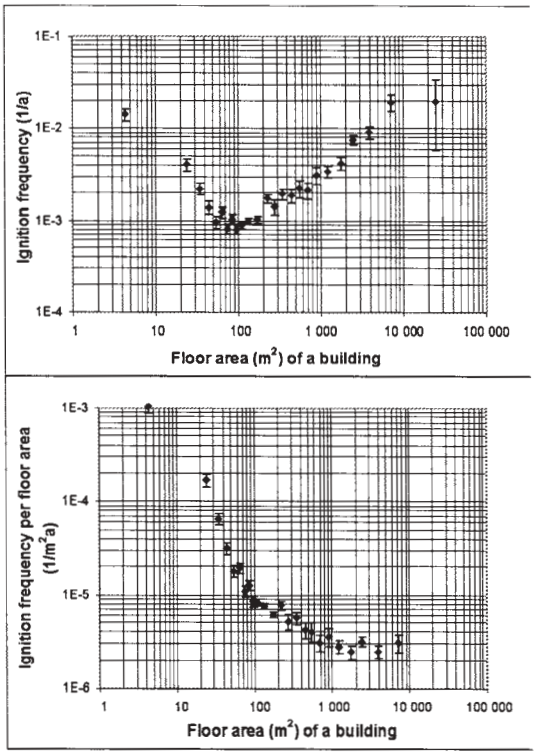


Figure 3.24: Fire occurrence frequency for all categories in Finland as a function of floor area of the building

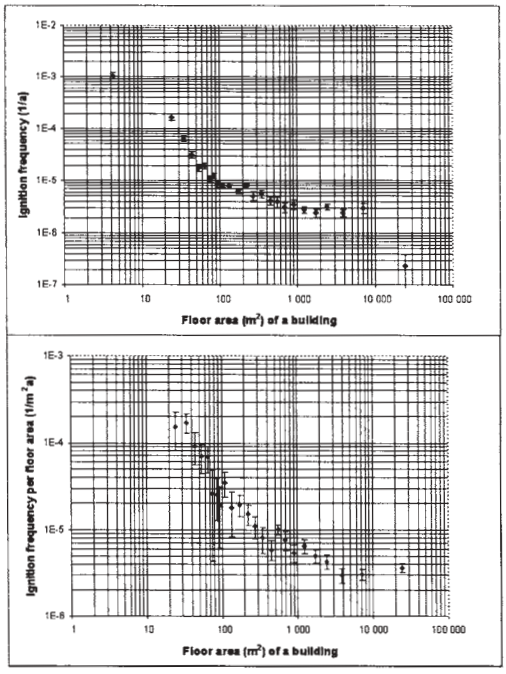


Figure 3.25: Fire occurrence frequency for all categories except dwelling buildings in Finland as a function of floor area of the building

3.5 NFSC - REAL FIRE DATABASE

A questionnaire (see below) was given to all members of NFSC and the advisory board with the goal of establishing a database of recent real fires (items 1 - 0) and for the evaluation of new buildings (items 1 - 6).

The questionnaires returned to WG4 are given in Annex A.

NFSC - WG 4 Fire Database Questionnaire

For new buildings please fill in 1 to 6
For buildings unfortunately exposed to a fire please fill in 1 to 9

1. Building

- Identification (Building, Street, City, Country) .....
- Sketch of building (Floor, Elevation, Situation in town (City map). Type of building (Z, V, G see Fig 1) .....

2. Fire compartment to be evaluated (critical room's e. g. room of "real fire" outbreak, largest room, room with special hazard as high fire load, concentration of people, rooms on highest floor and lowest floor, below ground level).
Identification: (utilisation of room, location in building)

length:	l = ...
width:	b =..... .....
height:	h =..... .....
floor level: (storey and floor height above / below ground)	e =..... no:.....
Fire Resistance of structure (< R30, R30, R60, R90, R120)	R ... (R).....
Fire Resistance of compartmentation	R ... (REI) .....
Fire Resistance of slabs	R ... (REI) .....
Fire Resistance of facade	R ... (E, RE, REI) .....
Type of structure: combustible/non combustible	.....
Openings (A_m, h, b, h_{sills})	.....
Forced ventilation	.....
Wall (thickness d, type of materials)	.....
Roof (thickness d, type of materials)	.....
Floor (thickness d, type of materials)	

3. Occupancy / fire load

Type of occupancy:	.....
fire load in compartment:[MJ/m^2 floor area]	.....MJ/m^2:
Special hazards:	.....

4. Safety measures .....

4.1 Basic measures: .....

- Portable extinguishers: sufficient/insufficient
- Internal hose ports: sufficient/insufficient .....
- Type of water supply: .....
  - Amount of water from public network available ≥ 3.600 l (min, ≥ 1.800 l/min, ≥ 900 l/min .....
  - Minimal reserved water for fire in public system > 480 m^3, > 240 m^3, > 120 m^3 .....
  - Distance to nearest hydrant < 70 m, < 100 m, > 100 m .....
  - Personal instructed for adequate behaviour in fire situation: available/not available

4.2 Special measures:

- Detection
  - Guards (≥ two rounds per night) (round every two hours) .....
  - Automatic detection system (for all building areas/ partial protection) .....
  - Sprinkler system (for all building areas/partial protection) .....
  - Independent water system for sprinklers .....
- Alarm transmission:
  - Guard and telephone .....
  - Guard (min 2 persons 24 hours) and telephone .....
  - Automatic from detection system to public fire brigade .....
  - Automatic from sprinkler to public fire brigade .....
  - Automatic by special checked and rented safety telephone line to public fire brigade .....
- Fire brigade
  - Public
    1. ≤ 20 men .....
    2. ≥ 20 men .....
    3. ≥ 20 men + extinguishing car with tank .....
    4. ≥ 20 men + car with tank > 1200 l .....
    5. As 4. + ≥ 3 men in less then 5 min leaving fire brigade station with car > 1200 l .....
    6. As 4. + ≥ 5 men in less then 5 min leaving fire brigade station with car with tank ≥ 2400 l .....
    7. Professional fire brigade .....
    8. Large professional fire brigade (big city) with special equipment .....
  - Time to reach building
    - < 5 km (< 15 min) .....
    - > 5 km (< 30 min) .....
    - > 30 min .....
  - Access to building facade with heavy truck (ladder) possible

- Work fire brigade .....
  1. ≥ 10 men during work hours .....
  2. ≥ 20 men during work hours .....
  3. ≥ 20 men all time on workdays + nights .....
  4. ≥ 20 men all time on + 4 men picket on holidays and Sundays .....

5. Evacuation

- Number of people
  - Identification of critical room (name, location in building) .....
  - storey of room with these people .....
  - number of people in this room .....
  - number of people on this storey .....
  - ability of people (hospitals, prisons, asylums ...) .....
  - awakeness of people (Hotels, guesthouses...) .....
  - normal use (Exposition, schools, shops ...) .....
  - escape route for occupants according to nat. regulations .....
  - rescue route for fire brigade (special / by normal staircase and corridor) .....

6. Value

- Value at risk:
  - Value of building (at moment of fire) .....ECU
  - Cost of building (to be rebuilt after fire) .....ECU
  - Value of building content .....ECU
  - Number of people in building at outbreak of fire .....ECU
  - Mean number of people in building (day / night) ..... / .....

7. Loss

- Damage to building ..... ECU
  - Cause of damage (% estimate fire / smoke / water) Fire: .....% / Smoke: .....% Water:..... .....%
- Damage to content ..... ECU
  - Cause of damage .....
- Damage to people .....
  - killed
  - injured

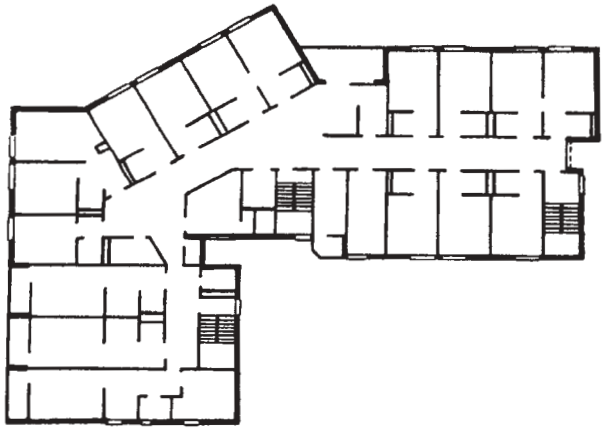
8. Fire

- Time and day (Monday ... Sunday) of fire start .....
- Place of outbreak .....
- Cause of fire (Arson, Electricity ...) .....

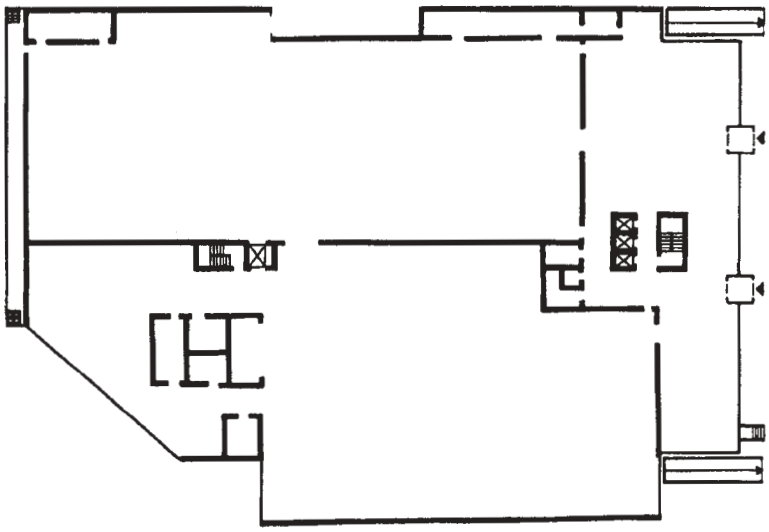
9. Response of fire brigade

- time to give alarm Min
- time: from alarm received to application of water Min
- no. of fire men at site of fire .....

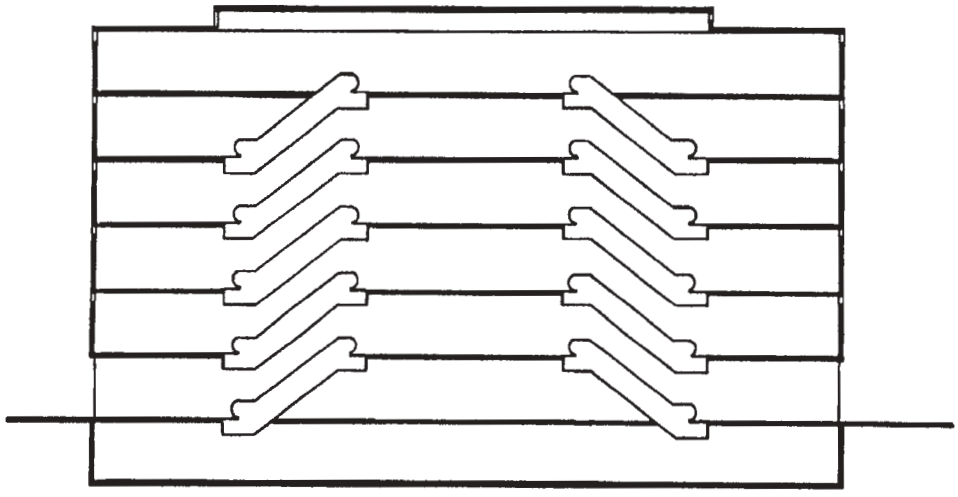
Building type Z



Building type G



Building type V



3.6 LUXEMBOURG FIRE BRIGADE DATABASE

The Luxembourg fire brigade report for 1995 and 1997 lists the following actions

3.6.1 ATTENDANCE OF THE FIRE BRIGADE

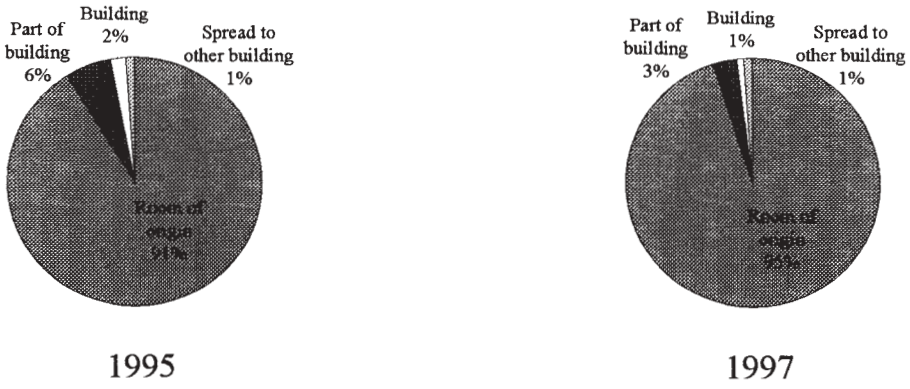
3.6.1.1 Type of action

	Number of responses 1995	1997
Fire in buildings	575	522
Car, trailer and machine fires	209	182
Forest, land and garbage fires	235	253
Others	406	650
Total	1643[1)]	1607
	(514 Neighbouring aid)	(508)
Technical actions	8887	7910
	(233 Neighbouring aid)	(531)

[1)] The number of fires is smaller than the number of responses reported by the 13 fire brigade associations of Luxembourg. In cases where neighbouring fire brigades come to help the local fire brigade each of the associations reports the case.

3.6.1.2 Extent of damage

	Number of cases 1995		1997	
Room of origin	1042	91 %	1641	95 %
Part of building	66	6 %	48	3 %
Building	24	2 %	26	1 %
Spread to other buildings	14	1 %	11	1 %
Total	1146	100 %	1726	100%



1995 1997

Figure 3.26: Extent of damage

3.6.2 DURATION OF THE ATTENDANCE'S OF THE FIRE BRIGADE

	1995			1997		
	number of attendance's	duration of attendance [hours]	average duration [hours]	number of attendance's	duration of attendance [hours]	average duration [hours]
Luxembourg town	485	395	0,81	502	382	0,76
Luxembourg country	115	220	1,91	139	222	1,60
Capellen	110	185	1,68	113	220	1,95
Esch	432	693	1,60	505	692	1,37
Mersch	56	164	2,93	81	210	2,59
Clerf	43	247	5,74	47	202	4,30
Diekirch	121	229	1,89	85	134	1,58
Vianden	17	52	3,06	6	27	4,50
Redingen	41	116	2,83	55	125	2,27
Wiltz	58	130	2,24	43	96	2,23
Echternach	41	105	2,56	31	59	1,90
Grevenmacher	67	145	2,16	72	247	3,43
Remich	58	90	1,55	61	130	2,13
total	1644	2771	1,69	1740	2746	1,58

Table 3.7: Duration of the attendance's of the fire brigade for different regions

4 SPRINKLER DATABASE

A large amount of statistical data is available for sprinkler systems. However some data is rather old and does not reflect the improvement made in sprinkler technology in recent years. An excellent summary was published by J. Dowling and J. Robinson in "Fire Prevention Journal" [18].

4.1 SUMMARY OF DATA FROM "FIRE PREVENTION JOURNAL" MARCH 1993

4.1.1 RELIABILITY OF SPRINKLERS

- USA NFPA[2] 96 %
- FM[3] 86 %
- New York 98 %
- Australia 99,5 %
- UK 94 %
- CH no failure since 15 years[4]
- D 98 %[4]
- FIN 99,5 %[4]

4.1.2 NUMBER OF HEADS OPERATING IN SPRINKLERED FIRES

Number of Heads	Australia	USA	Germany	Finland	France	Europe
1	65 %	28 %	40,7%		48,0 %	40,5 %
2	80 %	46 %	55,1%		61,3 %	57,5 %
3	86 %	56 %	69,6%		76,0 %	65,7 %
4	90 %	64 %	81,2%		78,0 %	72,2 %
5	92 %	69 %	----	58,3%	84,0 %	74,9 %
10	96 %	83 %	91,3%	90,3%		

Table 4.1: Number of heads operating in sprinklered fires

4.1.3 LOSS REDUCTION

NFPA (Depending on occupancy) 43 to 74 % (see also Table 4.2)
FM Average 77 %

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[2] US National Fire Protection Association (1925 to 1996)
[3] Factory Mutual Research: This figure reflects the insurance companies equivalent of a no claims bonus system. To avoid increases in their premiums, many building owners do not report fires that have been controlled by a small number of sprinkler heads. Consequently, a significant number of successful sprinkler operations incurring small losses are probably not reported (see [18] and 4.7.5).
[4] Data added by WG4 (see 3.2 and 3.3)

4.2 DATA FROM USA [24]

4.2.1 SPRINKLER STATISTICS FOR USA

The highest levels of sprinkler usage in high-occupancy properties appear to be in hotels, offices and in facilities that care for the aged and those that care for the sick. High-rise hotels, apartments and general office buildings (that is, those that are at least seven storeys high) are much more likely than their shorter counterparts to be equipped with sprinklers.

Property use		1982	1991
Public	all	13,5 %	19,8 %
Education	all	12,6 %	18,1 %
Health care facilities	all	36,7 %	48,7 %
Residential	all	1,0 %	2,5 %
	one and two family dwellings	0,2 %	0,8 %
	apartments	3,8 %	6,1 %
	apartments at least 7 storeys high		25,8 %
	hotels	16,7 %	30,6 %
	hotels at least 7 storeys high		66,1 %
Stores and offices	all	12,2 %	19,2 %
	offices	12,8 %	22,0 %
	offices at least 7 storeys high		53,7 %
Industry	all	5,0 %	11,0 %
Manufacturing facilities		42,1 %	48,9 %
Storage facilities		3,4 %	4,9 %
All structures		4,0 %	6,0 %

Table 4.2: Percentage of fires estimated to have occurred in structures with automatic suppression equipment

4.2.2 RELIABILITY (MAINTENANCE)

Table 4.3 is based on 3134 fires reported to NFPA during 1925 to 1969 for which sprinkler performance was deemed unsatisfactory ("Fire Journal", July 1970, page 37).

Problem		Percentage of cases	
Failure to maintain operational status of system		53,4 %	
	Water shut off		35,4 %
	Inadequate maintenance		8,4 %
	Obstruction to water distribution		8,2 %
	System frozen		1,4 %
Failure to ensure adequacy of system for complete coverage of current hazard		21,6 %	
	System not adequate for level of hazard in occupancy		13,5 %
	System designed for partial protection only		8,1 %
Defects affecting but not involving sprinkler system		15,9 %	
	Inadequate water supplies		9,9 %
	Faulty building construction		6,0 %
Inadequate performance by sprinkler system itself		5,6 %	
	Antiquated system		2,1 %
	Slow operation		1,8 %
	Defective dry-pipe-valve		1,7 %
Other		3,6 %	
	Exposure to fire		1,7 %
	Other or unknown		1,9 %
Total		100,0 %	

Table 4.3: Percentage of fires estimated to have occurred in structures with automatic suppression equipment

4.2.3 DAMAGE

The absence of multiple-death fires is a clear testimony to the value of sprinklers. The NFPA has no record of a fire killing more than two people in a completely sprinklered building (for public assembly, educational or residential) where the system was operating properly, except in the case of explosion, flash fires and casualties to the members of the fire brigade (for mercantile and industrial properties).

	without sprinkler			with sprinkler			percent reduction
Property use	fatalities	number of fires	fatalities per 1.000 fires	fatalities	number of fires	fatalities per 1.000 fires	%
Public assembly	170	130.900	1,3	3	25.800	0,1	91
Health care facilities	103	24.300	4,2	71	34.400	2,1	51
Hotels	283	37.800	7,5	30	11.400	2,6	65
Offices and stores	212	192.600	1,1	15	36.800	0,4[5]	65
Manufacturing facilities	138	70.700	2,0	76	61.700	1,2	37

Table 4.4: Sprinkler impact on life safety (NFIRS and NFPA 1982-91)

Firstly, sprinklers usually reduce the rate of fire deaths per thousand fires and the average loss by one-third to two-thirds, respectively. Secondly, the impact that sprinklers have on the death rate depends to some degree on how low the basic fire risk is in the property before sprinklers are added. Thirdly, the table may be very sensitive to the effect of one major fire if the basic risk is low so that this table is only meaningful for properties that have a substantial number of fatal fires.

	without sprinkler			with sprinkler			percent reduction
Property use	loss 10^6 US$	number of fires	loss per fires US$	loss 10^6 US$	number of fires	loss per fires US$	%
Public assembly	2.112	130.900	16.100	160,7	25.800	6.200	61
Health care facilities	58,3	24.300	2.400	27,5	34.400	800	65
Hotels	385,9	37.800	10.200	50,6	11.400	4.500	56
Offices and stores	3.474,7	192.600	18.000	385,6	36.800	10.500	42
Manufacturing facilities	1.964,4	70.700	27.800	798,7	61.700	12.900	53

Table 4.5: Sprinkler impact on property damage (NFIRS and NFPA 1982-91)

[5] Based on fewer than two deaths per year in the entire 10-year period. Results may not be statistically significant.

4.3 DATA FROM FINLAND [25]

4.3.1 BACKGROUND

- Number of sprinkler heads in Finland about 2,6 Mio in 1995 (1985: 1,5 Mio). The majority of industrial and commercial premises have been sprinklered.

- Total value of sprinklered premises approx. 51.000 Mio ECU[6].

- In 1985-1995 there were 60 to 100 fires in sprinklered premises, most of them in buildings of the pulp and paper industry or at sawmills and factories producing plywood or fibre board.

- Average fire loss in sprinklered premises per year 170. - 340.000 ECU (plus one big fire of 850.000 - 4,25 Mio ECU every 3 years).

- The financial losses have been only about 10^{-4} of the total insured value of the sprinklered premises.

- Total loss due to fire (all fires in Finland) ~ 100 Mio ECU/year.

- Water leakage
  In 1995, 195 cases of water damage with a total loss of approx. 35.000 ECU were reported. The most significant causes were:
  - Mechanical damage 34,0 %
  - Frost 23,0 %
  - Excess heat 15,0 %

- No information is available to allow comparison of the safety of sprinklered or non-sprinklered premises of the same kind.

- Reliability
- Inspection of 500 sprinkler systems per year by FFIC show about 2 % non-operational systems (mostly valves closed).
- In about 2/3 of the fires suppressed by sprinklers, no losses have been reported to the insurance companies.
- From 1985 - 1995 in only 4 cases sprinklers did not operate as they should for a total of approx. 800 fires. Reliability: (1 - 4/800) = 99,5 %. There is no contradiction between the reliability of a sprinkler system not working in a fire (0,5%) and the reliability of a sprinkler system not working during a system check (2%) because inspections are more frequent than fires.

[6] 1 FIN = 0.1674 ECU (20.12.98)

- In the 1990's the number of cases with 11 - 20 sprinklers opening is unexpectedly high. However, most of these are from a single hazardous premise where the deluge system has been designed to spray water from many sprinklers immediately - in all cases the sprinkler system has been very successful as can be seen in the loss data of that category of cases.

- Reduction given by insurance companies for sprinkler.
  The reduction is 25 - 40 % for one water source; with two independent water sources the reduction may be up to 70 %.
  If sprinklers have been installed to compensate structural fire safety, the reduction is typically of the order of 20 % less (e.g. if unprotected steel was used where it would not otherwise be allowed). It should be noted, however, that this reduction varies case by case depending on the ratio of the value of the contents vs. the value of the building.

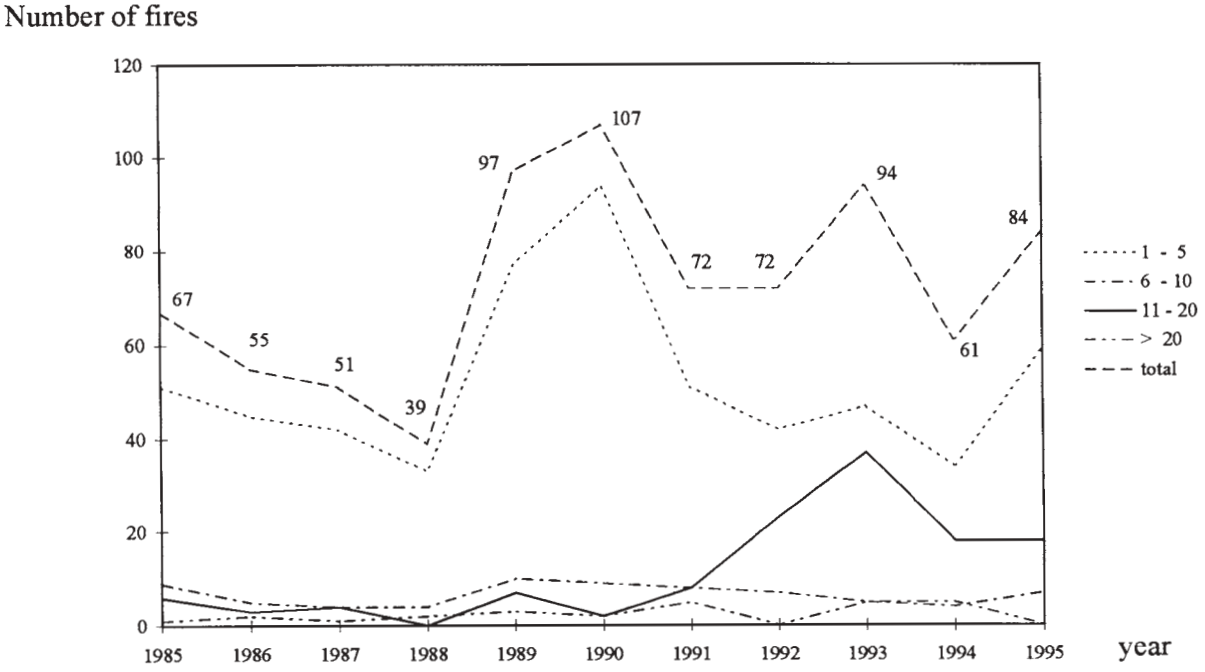

Figure 4.1: Number of sprinklers operating in Finland from 1985 to 1995

4.4 DATA FROM GERMANY

(Source: paper by U. Kirchner, August 1996, on the basis of data by "Bundesverband der Feuerschutzanlagenhersteller", BVFA and "Verband der Sachversicherer" VdS)

4.4.1 SPRINKLER STATISTICS FOR GERMANY

From 1971 to 1992 1490 fires in sprinklered premises were analysed. In 1459 cases the sprinkler system operated successfully.

Reliability 1459/1490 = 97,9 %
(for CO_2 - Systems the success ration for the same period was: 529 / 545 = 97,1 %)

open Sprinklers	Cases	%	Sum %
1 - 4	56	81,2 %	81,2
5 - 7	4	5,8	87,0
8 - 10	3	4,4	91,3
> 10	6	8,7	100,0

Table 4.6: Number of sprinklers open in case of fire (1992 BVFA data)

4.4.2 RELIABILITY (MAINTENANCE)

	1989	1990	1991	1992	1993
sprinkler systems:					
putting into operation	1.410	1.454	1.448	1.617	1.684
revisions	12.127	12.508	12.800	13.909	14.881
total	13.537	13.962	14.288	15.526	16.565
deficiencies	2.518	2.789	3.455	3.182	3.994
quota of deficiency	0,186	0,200	0,242	0,205	0,241

Table 4.7: Reliability of sprinkler systems(BVFA data)

In Germany all systems are inspected once a year. From the 14.881 systems checked in 1993, 3994 had a defect (which must not in all cases lead to sprinkler failure) 3994 / 16.565 = 0,241 = 24,1 %

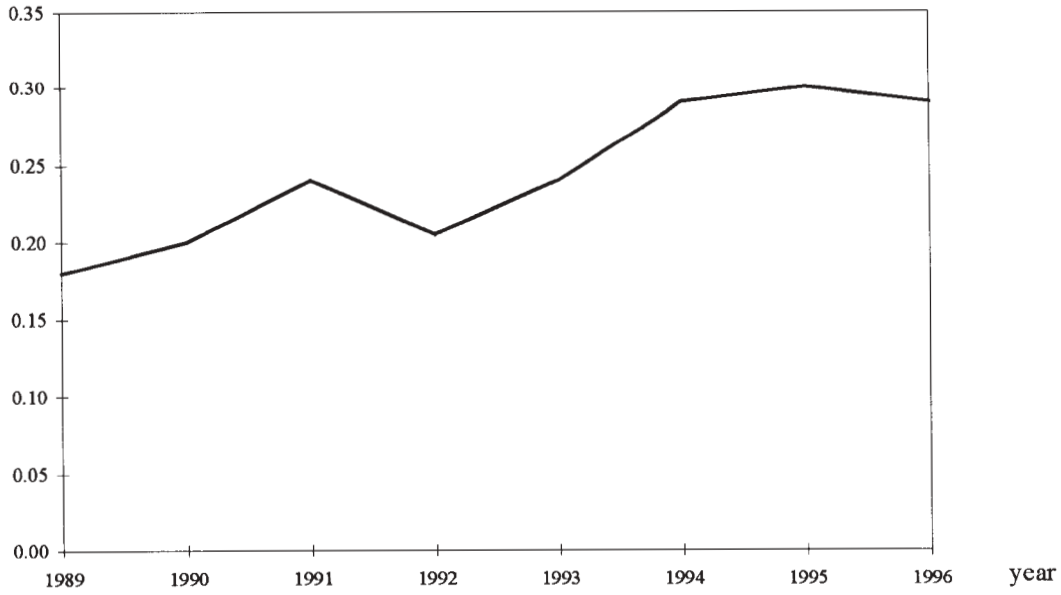

Figure 4.2: Proportion of deficient systems found during inspections in Germany (Data by VdS)

Type of defect:	Water supply	487	12,2 %
	Main valve	114	2,9 %
	Alarm system	979	24,5 %
	Change of utilisation	799	20,0 %
	Water distribution of sprinkler heads	1615	40,4 %
		3994	100 %

4.4.3 DAMAGE

The German Association of Insurers VdS has analysed the fires in sprinklered premises for 1991/92

Total number of analysed cases	70
in department stores	25
in the timber industry	7

In department stores the average damage was about 25.000 ECU with one case with a maximum of 160.000 ECU. In the timber industry one case with a maximum loss of 475.000 ECU occurred, the average being 125.000 ECU.

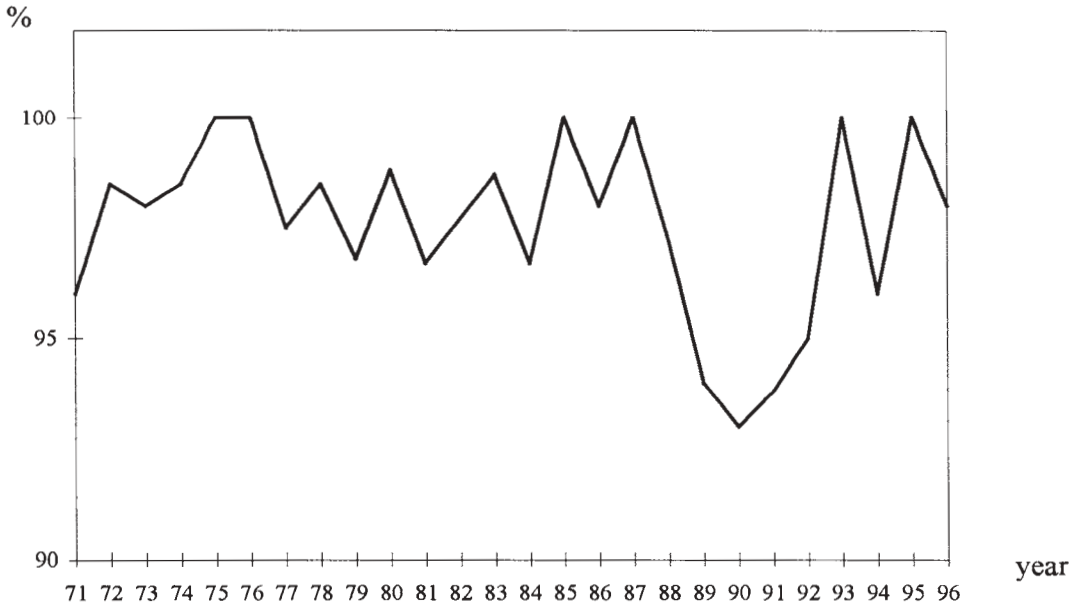

Figure 4.3: Rate of success of German sprinkler systems from 1971 to 1996 (Data by VdS)

Figure 4.4: Number of fires in sprinklered premises from 1971 to 1996 (Data by VdS)

4.5 DATA FROM FRANCE

(Source: APSAD, Assemblée Plenière des societés d'assurance dommages, Note d'information, Juillet 1997, Paris)

4.5.1 SPRINKLER STATISTICS FOR EUROPE

From 1985 to 1994, 1164 fires in sprinklered premises were analysed in the 13 countries (Austria, Belgium, Denmark, England, Finland, France, Germany, the Netherlands, Italy, Norway, Sweden, Switzerland, Turkey) of the CEA (Comité Européen des Assurances). It has to be noted that small fires controlled by few heads are often not reported to the insurers and are therefore not included in the statistics, while large fires are in general reported. Since 1987 the average number of heads operating in a sprinklered fire has not changed much.

The usual sprinklered area per control area is in the range 150 to 300 m^2 or between twenty and thirty sprinklers. A sprinkler system seems to be satisfactory if less than thirty sprinkler heads are open. This happened in 96 % in all cases. Table 4.8 shows that the performance of sprinklers has improved over the years.

Period	Number of fires	Number of heads operating	
		5 or less	30 or less
1970 - 1980	4763	69,2 %	93,3 %
1980 - 1984	1724	73,7 %	95,2 %
1985 - 1994	1164	74,9 %	96,0 %
1970 - 1994	**7651**	**72,6%**	**94,8 %**

Table 4.8: Number of opened sprinkler heads (Europe 1970 - 1994)

The malfunction is estimated from 4 to 5 % (50 % of all cases due to human error (closed valves...) and bad maintenance, 25 % due to the malfunction of the water supply and 25 % because the system was not adequate for the level of hazard in occupancy or designed for partial protection only).

Among the systems checked from 1985 to 1994, 1476 had a defect of water leakage.

Type of defect:	mechanical shocks	28 %
	corrosion	23 %
	overheating	15 %
	frost	15 %
	different reasons	19 %
		100 %

Of all the 1164 fires occurring in the years 1985 to 1994, 498 fires were analysed with regard to the loss caused by the fire. It was seen that 2/3 of all fires caused 2,5 % of the monetary loss. The average loss for fires where three or less sprinkler heads opened was 105.000 FF.

4.5.2 FRENCH SPRINKLER STATISTICS 1994 TO 1996

The results of statistics for France seem to be slightly better than for the average of Europe as a whole. But for a comparison it must be pointed out that the period in France was more recent and shorter (1994 - 1996, 75 fires in 3 years) than the period for Europe (1985 - 1994, 1164 fires in 10 years).

Number of Heads	Europe 1985 - 1994	France 1994 - 1996
1	40,5 %	48,0 %
2	57,5 %	61,3 %
3	65,7 %	76,0 %
4	72,2 %	78,0 %
5	74,9 %	84,0 %

Table 4.9: Number of heads operating in sprinklered fires

4.5.3 CONCLUSION

The statistics of France and Europe show that the positive impact of sprinkler systems is undeniable and the performance of sprinkler systems is increasing.

The most important reason for an excellent performance is a good design and maintenance of the system.

In all the 7651 fires in Europe during the years 1970 - 1984 with sprinkler system protection no casualties were reported.

4.6 DATA FROM AUSTRALIA [26]

4.6.1 AUSTRALIAN SPRINKLER STATISTICS 1886 TO 1986

This statistic is concerned with the overall performance of automatic sprinkler systems in the 9.022 fires for which detailed reports are available, and which occurred in the 100 years from 21st December, 1886 to 21st December, 1986. Table 4.10 gives the numbers of sprinkler heads operating on all fires expect the 49 fires not controlled.

Number of heads operating	number of fires	%	Number of heads operating	number of fires	%
1	5.816	64,55	28	5	0,06
2	1.431	15,86	29	5	0,06
3	553	6,13	30	5	0,06
4	290	3,21	31	4	0,04
5	189	2,09	32	3	0,03
6	144	1,60	33	4	0,04
7	87	0,96	34	1	0,01
8	76	0,84	36	2	0,02
9	50	0,55	37	3	0,03
10	47	0,52	39	2	0,02
11	22	0,24	40	1	0,01
12	24	0,27	41	1	0,01
13	31	0,34	43	1	0,01
14	32	0,35	44	1	0,01
15	22	0,24	46	2	0,02
16	12	0,13	48	1	0,01
17	11	0,12	54	2	0,02
18	22	0,24	56	3	0,03
19	12	0,13	62	1	0,01
20	2	0,02	67	1	0,01
21	5	0,06	71	1	0,01
22	7	0,08	72	1	0,01
23	7	0,08	74	1	0,01
24	13	0,14	77	1	0,01
25	4	0,04	87	1	0,01
26	4	0,04	90	1	0,01
27	4	0,04	94	1	0,01
			113	1	0,01
	8.917	98,87		56	0,59

Table 4.10: Number of heads operating in sprinklered fires

Sub-total	8.973	99,46
Fires not controlled	49	0,54
	9.022	100 %

Fires controlled with less than 31 heads: 8973 - 41 = 8932 (99%)

4.6.2 ANNUAL LOSS

It can be seen from Table 4.11 that the average annual cost of fire and water damage in buildings equipped with automatic sprinklers was AUD 337.138 in terms of the value of the Australian and New Zealand currencies at the end of 1967.

year	annual loss in AUD
1948	823.525
1949	60.947
1950	74.013
1951	470.502
1952	55.146
1953	203.500
1954	106.160
1955	169.780
1956	189.600
1957	146.160
1958	737.280
1959	164.480
1960	164.400
1961	893.740
1962	194.860
1963	298.440
1964	316.240
1965	504.720
1966	637.060
1967	532.200
total for 20 years	6.742.753

Table 4.11: Total annual loss from fire and water damage in buildings equipped with automatic sprinkler systems

It is extremely difficult to estimate what losses would have occurred if the sprinkler systems did not operate in specific buildings because of the many factors involved.

To arrive at a reasonable estimate of potential fire losses based on a similar range of occupancies to those in which fires involving automatic sprinklers occurred, but which were not equipped with automatic sprinkler systems, thermal alarms or smoke detectors, a detailed analysis of fires recorded in industrial, commercial, and institutional buildings in Australia and New Zealand for the calendar year 1967 was made, using the estimates of losses to buildings and contents issued at the time of the fires. These losses ranged from the lowest figure of AUD 3.000 to the highest of AUD 2.000.000 and the average was AUD 100.782 per fire. It seems to be reasonable to take approximately half of this figure or say AUD 50.000 per fire as a conservative estimate of the potential losses if the sprinkler systems did not operate in the building concerned.

Table 4.12 gives the number of fires in automatic sprinkler protected buildings reported for each year together with estimates for potential losses if the automatic sprinkler systems had not been installed, based on the foregoing figure of AUD 50.000 per fire.

year	numbers of fires	potential losses in the absence of automatic sprinkler system in AUD
1948	124	6.200.000
1949	162	8.100.000
1950	140	7.000.000
1951	189	9.450.000
1952	151	7.550.000
1953	150	7.500.000
1954	169	8.450.000
1955	160	8.000.000
1956	172	8.600.000
1957	196	9.800.000
1958	216	10.800.000
1959	189	9.450.000
1960	228	11.140.000
1961	176	8.800.000
1962	182	9.100.000
1963	239	11.450.000
1964	221	11.050.000
1965	253	12.650.000
1966	224	11.200.000
1967	240	12.000.000
total for 20 years		188.290.000
average per year		9.414.500

Table 4.12: Numbers of fires in automatic sprinkler protected buildings and estimates of potential losses if automatic sprinklers did not operate

4.6.3 CASUALTIES IN FATAL FIRES

In the hundred years 1886 - 1986 11 fatalities occurred, eight of them in flash fires or explosions. However, individual reports show that sprinklers have saved lives in a wide variety of adverse circumstances.

4.7 DATA FROM UK [27]

4.7.1 PERFORMANCE

The most common way of expressing sprinkler performance is the number of sprinkler heads that open in a fire. The fewer sprinkler heads opening the more effective sprinklers are.

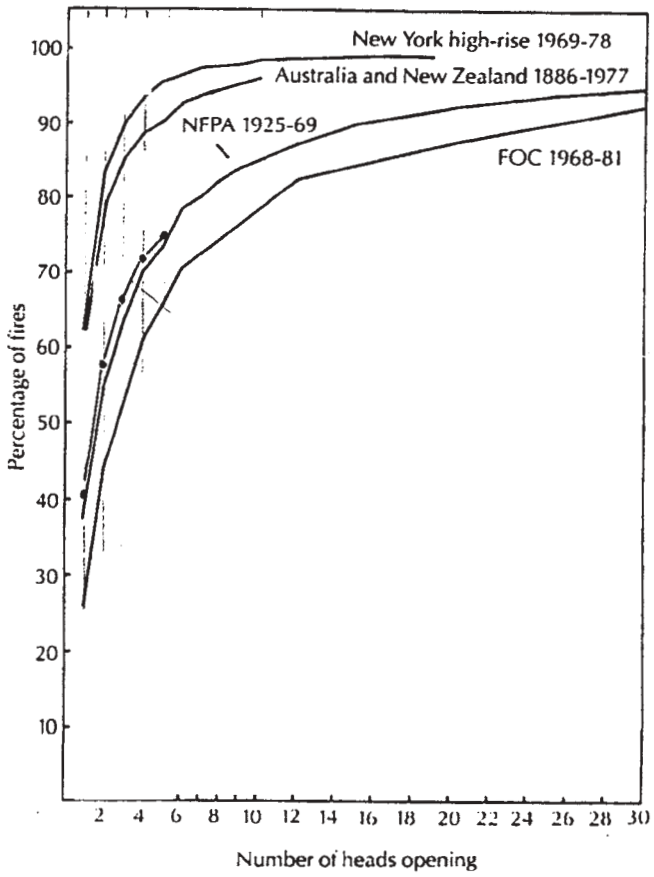

Figure 4.5: Differences in the performance record

Sample	Sample size	Reference	No. of heads opening – cumulative percentages																										
			1	2	3	4	5	6	7	8	9	10	11	12	13	14 or fewer	15	16	17	18	19	20	21	22	23	24	25	30	35	40
Australia and New Zealand 1886-1968	5734	1	66.6	82.1	88.0	91.2	92.8	94.1	94.9	95.7	96.1	96.7	96.9	97.2	97.4	97.7	97.9	–	–	–	–	98.4	–	–	–	–	98.8	99.0	99.0	99.1
Australia and New Zealand 1886-1973	Not stated (Approx. 6984)	2	65.9	81.8	87.6	90.8	92.5	93.9	94.7	95.5	95.9	96.5	96.7	97.0	97.2	97.6	97.9	–	–	–	–	98.3	–	–	–	–	98.7	98.9	99.0	99.1
Australia and New Zealand 1886-1977	7707	3	64.1	79.3	85.5	88.7	90.3	92.9	93.7	94.8	95.3	95.8	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Australia and New Zealand 1968-77	1973	3	61.6	76.4	82.9	86.2	87.8	91.9	92.5	93.9	94.4	94.9	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
New York high-rise office 1969-78	250	4	71.6	87.2	95.6	96.0	98.4	99.2	–	–	–	99.6	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
New York high-rise (not office) 1969-78	1364	4	64.1	83.9	90.4	93.9	95.7	96.8	97.9	98.2	98.4	98.8	98.9	99.3	99.3	99.5	99.6	99.6	99.8	99.9	–	–	–	–	–	–	–	–	–	–
New York low-rise 1969-78	3866	4	55.8	72.7	80.5	85.5	88.6	90.6	91.7	92.9	93.3	94.0	94.3	94.8	95.1	95.4	95.7	96.0	96.1	96.3	96.4	96.7	96.7	96.8	96.8	96.9	97.1	97.4	–	97.5
NFPA 1925-69	79 544	5	37.4	54.6	63.8	70.1	73.4	77.7	80.1	82.2	83.7	85.0	86.2	87.3	88.0	89.0	89.7	–	–	–	–	92.2	–	–	–	–	93.6	94.8	95.5	96.2
NFPA wet systems	54 158	5	42.6	61.0	70.2	76.2	80.2	83.2	85.2	87.0	88.3	89.4	90.4	91.2	91.7	92.6	93.1	–	–	–	–	95.0	–	–	–	–	96.0	96.9	97.3	97.7
NFPA dry systems	13 217	5	20.1	32.7	41.5	48.7	53.7	57.8	61.3	64.2	66.4	68.5	70.3	72.4	73.8	75.3	76.2	–	–	–	–	81.0	–	–	–	–	84.3	86.7	88.6	90.0
Mather and Platt 1946-64	1110	6	38.8	55.2	64.0	69.4	72.6	76.0	78.7	81.0	83.0	83.8	85.0	86.9	87.4	88.6	89.3	89.9	90.5	90.9	91.4	91.9	–	–	–	–	93.3	94.9	96.0	96.9
Mather and Platt wet systems	Not stated	6	40.6	57.3	65.5	71.5	74.7	78.0	80.9	82.9	84.8	85.7	86.7	88.4	88.8	90.0	90.3	90.7	91.0	91.6	92.0	92.6	–	–	–	–	93.6	94.9	96.0	96.8
Mather and Platt dry systems	Not stated	6	30.1	44.8	55.7	58.5	62.3	65.6	67.8	71.6	73.8	74.3	76.0	79.8	80.3	81.4	84.2	85.8	87.4	87.4	88.0	88.5	–	–	–	–	91.8	94.5	96.2	97.3
CEA 1968-81	5118	–	32.8	48.3	58.8	65.7	70.1	74.1	–	–	–	–	–	84.6	–	–	–	–	–	89.2	–	–	–	–	–	–	–	93.5	–	–
FOC 1968-81	2683	–	26.4	43.8	55.3	61.5	66.5	70.8	–	–	–	–	–	82.8	–	–	–	–	–	87.6	–	–	–	–	–	–	–	92.6	–	–

Table 4.13: Number of heads opening in fires

4.7.2 INFLUENCE OF STANDARDS

Differences in the standards to which sprinkler systems are built and installed appear to have minimum influence (see Figure 4.4). A reason for this small difference is that systems classified as not in accordance with the rules are mostly systems built to old but nevertheless rigorous sprinkler standards.

From the data available there is no discernible variation between fusible link and glass bulb sprinklers.

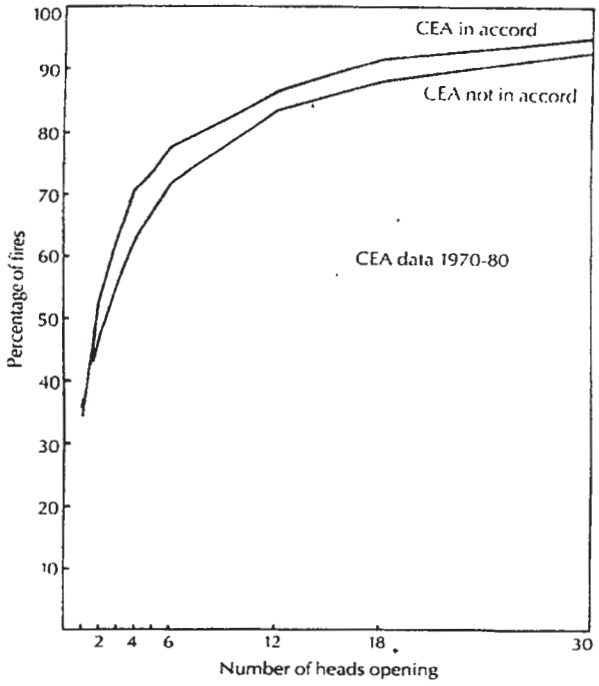

Figure 4.6: Effect of non-standard systems

4.7.3 INFLUENCE OF OCCUPANCIES

The performance of sprinkler systems varies greatly between different occupancies. Fires in 'high-risk' occupancies open a greater number of sprinkler heads.

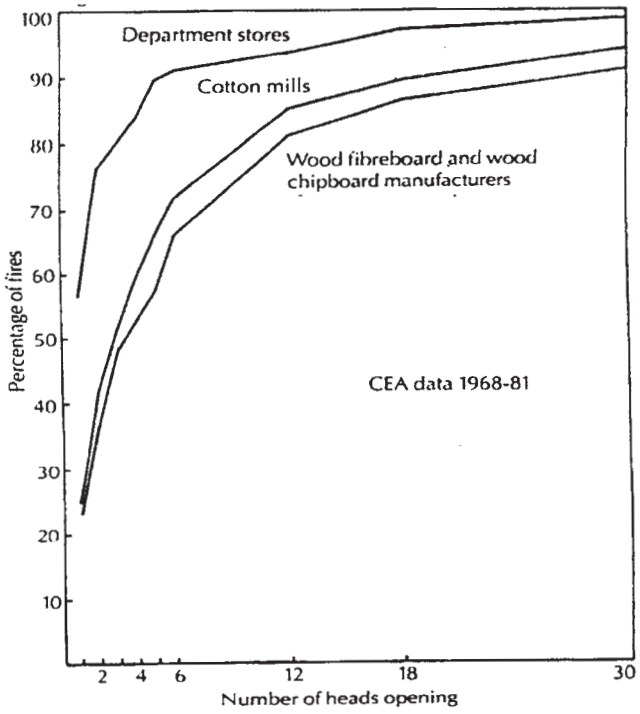

Figure 4.7: Effect of different occupancies

4.7.4 WET AND DRY SYSTEMS

Dry systems show a poorer performance than wet systems. There is a delay before dry system discharges water. In addition dry sprinklers are particularly used to protect unheated areas likely to be used for storing goods that lead to quickly developing fires.

4.7.5 COMPLETENESS OF RECORDS

Major fires are almost always reported while small fires opening one or a few heads may not be reported to the fire brigade and the insurance companies. The data thus becomes biased towards the larger fires and shows sprinklers in a less favourable light than is really the case. This is the most probable explanation for differences in sprinkler performance.

Australia and New Zealand data are nearly complete as in 98% of fires the fire brigade is called automatically because the alarm valve is connected to the fire brigade.

New York data is believed to be complete, as the fire patrol reports to almost all fires in sprinklered buildings.

NFPA data relies on the goodwill of fire departments to notify NFPA on sprinkler fires. Because data is incomplete and biased towards large fires NFPA stopped collecting after 1970. CEA and FOC data are incomplete because not all small fires are reported and are therefore biased towards larger fires [10].

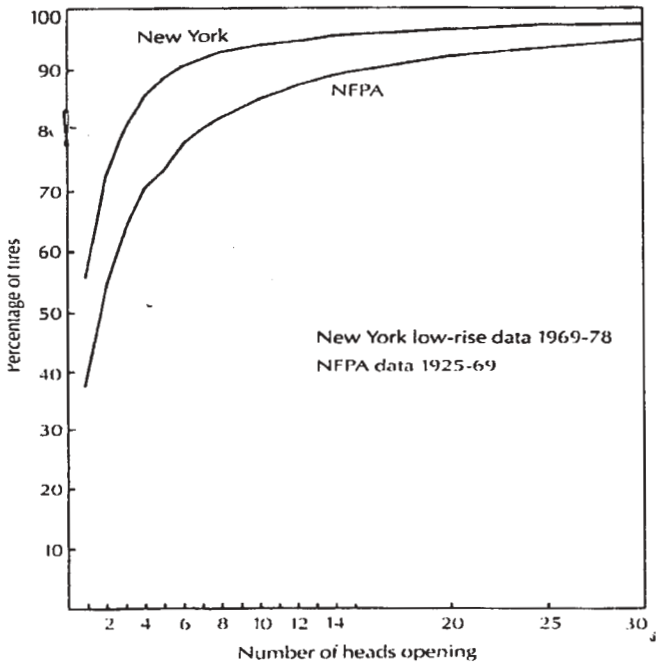

Figure 4.8: National dissimilarities New York (data complete) and NFPA (data biased towards large fires) compared

This difference becomes obvious by comparing the data for New York low-rise buildings and the overall American data from NFPA. The difference may be attributed to the fact, that small fires are not included in the NFPA reports.

4.7.6 IMPORTANT PARAMETERS FOR SPRINKLER RELIABILITY

The above average success of Australian sprinklers may be explained by:
- Automatic alarm to fire brigade if sprinklers open
- All plans of sprinkler systems checked by rating offices
- Installed sprinkler systems tested against specification by rating bureau
- The sprinkler systems checked weekly (control valve, water supply, alarm) with written report
- Electronic scanning in high-rise buildings

In Switzerland all alarm valves are connected to the fire brigade. Closing the main valve will transmit an alarm to the fire brigade preventing the closed valve syndrome and closing the valve in case of intended arson.

4.7.7 OVERALL SUCCESS RATE

The performance criterion of opening sprinkler heads does not include closed valves. Table 4.14 gives an overview based on the undefined term 'control':

Sample	Source	Success criterion	Percentage successful
Australia and New Zealand 1886-1977	[28]	Less than 20% of buildings and contents damaged	99,6 } 99,5
Australia and New Zealand 1886-1981	H. Marryatt Private communication	'Control'	99,4
NFPA 1925-69	[31]	'Control'	96,2
New York low-rise buildings 1969-78	[30]	'Control'	95,8
New York high-rise buildings 1969-78	[30]	'Control'	98,8
UK fire brigade 1966-73	[43]	'Control'	94,3-95,3 (95,4-96,2 when corrected for unreported fires)

Table 4.14: Overall success rates

An estimate by the Home Office Scientific Advisory Branch HOSAB comes to an overall success rate of 95,4 to 96,2% including 20% of unreported fires. The number of unreported fires may be higher and therefore the true success rate may be more than 96%.

4.7.8 CONCLUSIONS

'Imprecisely, however, there can be no doubt about sprinkler success. Sprinklers are extremely successful in controlling and extinguishing fires.'

4.7.9 REFERENCES TO CHAPTER 4.7

References are listed in chapter 7 from [26] to [42].

5 CONCLUSIONS

5.1 FIRE OCCURRENCE AND FIRE GROWTH

On the basis of nearly 40.000 fires in Berne from 1986 to 1995 (see chapter 2.2) the frequency of fire occurrence and fire growth is estimated in function of the size of loss to the building structure reported (Table 2.5 and Table 2.6) and the floor area (Table 2.7). Table 5.1 shows the frequency of fire occurrence and growth to a given loss size. For example the frequency of a fire to start in an industrial building was found as $11,6 \cdot 10^{-6}$ / (m^2 • year) and the frequency of fires to start and to grow as large as to cause a loss to the building structure of more than 99.999 CHF is $0,85 \cdot 10^{-6}$ / (m^2 • year). A decrease of the fire occurrence frequency with increasing compartmentation or building size was not studied, the frequencies are average values over the whole building group of Berne.

Loss-size	All [10^{-6}] / (m^2 • year)	Dwellings [10^{-6}] / (m^2 • year)	Office / Public [10^{-6}] / (m^2 • year)	Industrial [10^{-6}] / (m^2 • year)
All losses	32,3	33,3	10,60	11,6
> 1.999	9,18	9,22	4,35	6,48
> 49.999	0,927	0,710	0,40	1,32
> 99.999	0,641	0,460	0,27	0,85

Table 5.1: Frequency of fire occurrence and growth to a given loss size [per m^2 • year] for different occupancy classes

Data on the frequency of fire occurrence depends on the minimum size of fire which is counted in statistics as a fire. Ergo the data of GVB takes every reported fire into account even if there was no fire brigade action (see 2.3.1) while insurance reports of industrial insurers with high excess do often include less fires than the fire brigade reports.

Further a decrease of the fire occurrence frequency per floor area in buildings with large compartments seems to be noted (see 3.4). An exponent < 1,0 is proposed in literature [14, 19, 20].

In Table 5.2 the values of the fire occurrence frequency for different occupancies in the Canton of Berne given in Table 5.1 are compared to data from other sources.

In V DIN 18230 (1987) and its background document [2, 16] the fire occurrence rate for industrial buildings was given as $2 \cdot 10^{-6}$/(m^2 • year) and has now been increased to $10 \cdot 10^{-6}/m^2$ in the 1996 draft edition E DIN 18230 [17]. Compared to the data in Table 2.8 the new value corresponds to fires with a damage larger than 500 CHF. In the recently published BSI document DD 240 part 1 "Fire safety engineering in buildings" [3] annex B gives selected data for use in a probabilistic risk assessment.

Probabilities of fire starts related to floor area are given in Table B.2 and B.3. For a basic floor area of 1000 m^2 Table B.3 gives the probability of fire starts in industrial buildings as 66 • 10^{-6} per m^2 • year which is 6 times higher than found in our survey on the basis of all fires reported or according to the new German data. This was already noticed by the authors of the German data [19] and attributed to national differences. Another explanation may be found in the age of the building (see Figure 2.5). Finish and French data for industrial buildings are similar to the findings from Berne.

Frequency of fire occurrence						
Country	All [10^{-6}] / (m^2 • year)	Dwellings [10^{-6}] / (m^2 • year)	Office / Public [10^{-6}] / (m^2 • year)	Industrial [10^{-6}] / (m^2 • year)	Number of registered fires	Remarks
Berne all > 1.999 > 49.999 (see 2.2)	32,3 9,18 0,93	33,3 9,22 0,71	10,6[7] 4,35 0,40	11,6 6,48 1,32	39.104 in the Canton of Berne (1986-1995)	due to the monopoly all fires are included[8]
FIN [13] (see 4.3)	7,2	7,1[9]	1,7[10] Public = 3,1 ... 9,5	11,0	2.109 (1995) total number of buildings 1.150.494	data only collected by the fire brigades (estimated 75% of all fires)
UK [3, 14]			12,0[11]	66,0		
BRD [2, 17] DIN 18230 (1987) DIN 18230 (1996)				2,0 10,0		There is no background on the information
France[12]		21,2[13]	8,9[14]	7,9[15]		

Table 5.2: Comparison of the Swiss data with other countries

[7] Including office and public buildings
[8] From the data of the fire brigade it can be seen that the fire brigade is called out to only 40% of all fires reported in the GVB statistics. Therefore the fire occurrence rate from the fire brigade reports is smaller than the calculated from the GVB insurance report.
[9] Only residential buildings
[10] Institutional buildings (e.g. hospitals) 9.5, educational buildings 3.1, public buildings 4.6
[11] Office buildings according to information of the USA quoted in BSI [3]
[12] See chapter 3.1, table 3.4
[13] Including offices and dwellings
[14] Only public
[15] Industrial buildings and warehouses (see 3.1.2.5.1)

The failure rate of limiting fire growth is estimated in Table 5.3. From the fact that only 40% of fires are attended by the fire brigade (see chapter 2.3.3) fires with a loss < 1.999 CHF are considered to be controlled by the occupants or were self-terminated. For the fire brigade the criterion control of fire could be related to a loss of < 49.999 CHF in general and for buildings with large compartments (industrial) to < 99.999 CHF.

failure rate of limiting the fire growth	All	Dwellings	Office / Public	Industrial
occupants e.g. fire loss > 1.999 CHF	28,4 %	27,7 %	41,0 %	56,1 %
fire brigade (one room) e.g. % of all the fires that grow to over a loss of 49.999 CHF if loss > 1.999 CHF	10,1 %	7,9 %	9,2 %	20,3 %
fire brigade (part of building) e.g. % of all the fires that grow to over a loss of 99.999 CHF if loss > 1.999 CHF	7,1 %	5,0 %	6,2 %	13,3 %

Table 5.3: Failure rate in limiting the fire growth

On this basis the fire brigade factor of 0,1 given in DIN 18230 [2] for industrial buildings seems to be justified (e.g. from Table 5.3 it can be seen that 13,3% of fire not controlled by occupants grow larger than 99.999 CHF in industrial buildings). In dwellings fire brigade success is even better.

Table 5.4 shows the extent of damage (e.g. the limit of fire growth) from Luxembourg and UK and compares this data to our survey of the 40.000 fires in the Canton of Berne. Only 6% (Lux) to 10,5% (UK) of fires grow to a state causing severe damage or destruction to the building structure. The data of Berne (7,3%) is in between Luxembourg and UK data.

The national differences may reflect an increase in fire safety during the last years, as Luxembourg and GVB data is more recent than BSI data.

Extent of damage	LUX[16] 1995 %	BSI[17] %		GVB[18] [CHF]	%	
No damage	} 94,0	70,0	}89,5	< 1.000	52,3	
				< 2.000	71,6	]
Slight		12,0		2.000 to 4.999	15,4	] 92,7
Surface		7,5		5.000 to 9.999	5,7	]
Severe	3,0	7,5		10.000 to 49.999	4,4	
Destruction	3,0	3,0		> 50.000	2,9	
				> 100.000	2,0	

Table 5.4: Fire growth: Comparison of the extent of damage from different statistical sources

5.2 SPRINKLER

The performance of sprinklers is often expressed in terms of the number of sprinkler heads opening in a fire. Based on the set of sprinkler data given in chapter 4.6 (Table 4.10) less than 30 heads will open in more than 99% of the cases. Taking into account even the cases with shot valves for well checked systems an overall reliability of 96 to 99% can be assumed. The value to be taken into account depends on various parameters (see e.g. chapter 4.1.1). As default value 98% seems appropriate.

This performance is higher than that of fire compartmentation especially if doors or other openings are present, because there is rarely a mandatory periodical maintenance and inspection for passive measures. Even though limited in number and restricted to large losses the Dutch data shows that from the 23 cases where compartmentation was present it failed in 11 cases e.g. 48%, while in none of the cases a sprinkler failed.

[16] A detailed description of the extent of the damage is missing in the Luxemburg Fire Brigade Database (see chapter 3.6)

[17] see chapter 2.3 table 2.12

[18] see chapter 2.2.4.2 table 2.3

6 RECOMMENDATIONS

6.1 FIRE OCCURRENCE AND FIRE GROWTH

The probability of a severe fire able to endanger the structural stability may be expressed as:

$$p_{fi} = p_1 \cdot A^x \cdot p_2$$

with: p_1 : probability of severe fire including the effect of the occupants and a public fire brigade
p_2 : reduction factor if sprinkler system is present
A : surface area of compartment
x : exponent $\leq 1{,}0$

Note: The factor p_1 includes the actions of the occupants and the public fire brigade in preventing a fire to grow into a severe fire and is not to be mistaken as the frequency of fire occurrence.

For the application in the NFSC method the following default values are recommended.

Occupancy	p_1 [10^{-6}/(m^2 ·year)]	Exponent x[19]
Office	0,2 - 0,4	0,75 - 1,0
Dwelling	0,4 - 0,9	1,0
Industrial	0,5 - 1,0	0,3 - 1,0

Table 6.1: Probability of fire start and growth to severe fire with public fire brigade present

Reduction factor for sprinkler system:

Type of sprinkler	p_2
Normal (e.g. according to the regulations)	0,02
High standard (e.g. electronically checked valve, two independent water sources)	0,01 - 0,005
Low standard (e.g. not according to the regulations)	≥ 0,05

Table 6.2: Reduction factor for sprinkler system

[19] See chapters 3.2 and 3.4. The Berne data has not been analysed with regard of the area dependency. Until such data is available a conservative value of 1.0 is recommended when applying p_1 based on the Berne data.

6.2 EVENT TREE ANALYSIS

Alternatively an event tree may be established from fire start to describe fire growth, using recommended default values from Table 6.3.

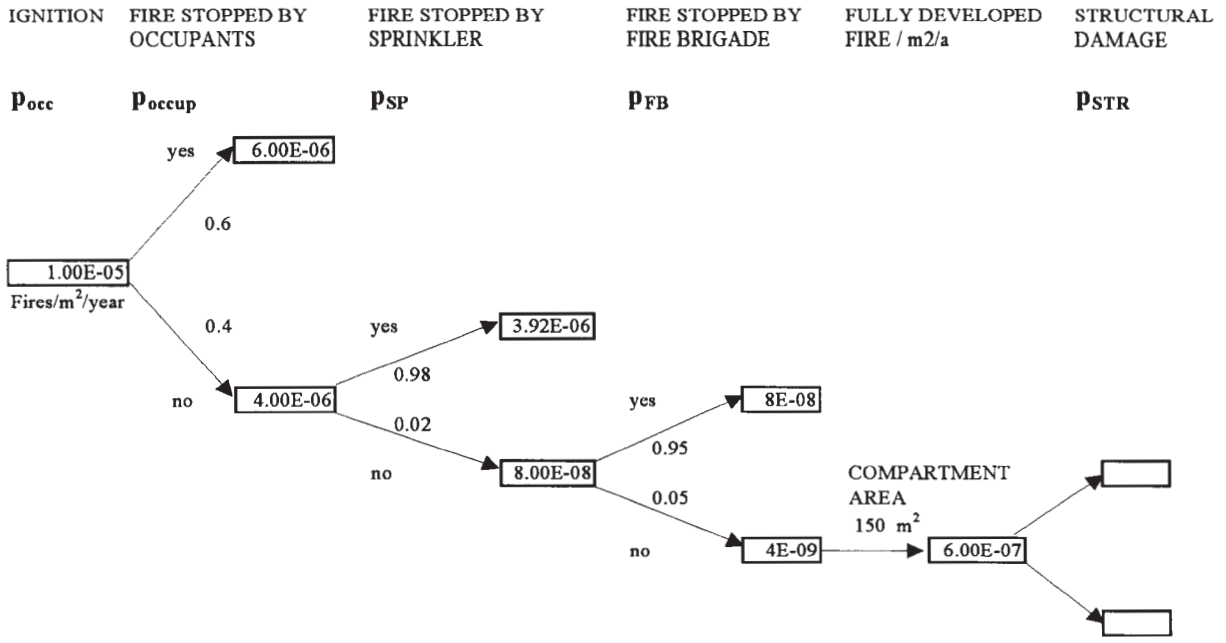

Figure 6.1: Example for an event tree for fire growth in an office with a compartment area of 150 m^2

From Tables 6.1 and 6.3 the following factors may be recommended:

		Dwelling	Office	Industrial
Fire occurrence	p_{occ}	$30 \cdot 10^{-6}$	$10 \cdot 10^{-6}$	$10 \cdot 10^{-6}$
Fire stopped by occupant	p_{occup}	0,75	0,60	0,45
Fire stopped by sprinkler system	p_{SP}[20]			
Fire stopped by fire brigade	p_{FB}	0,90 - 0,95	0,90 - 0,95	0,80 - 0,90
Fire confined by structure	p_{STR}[21]			

Table 6.3: Event tree factors

[20] see table 6.2
[21] to be calculated by structural analysis

P_{FB}, the probability that the Standard Fire Brigade manage to stop the fire, is between 0,9 and 0,95 for Offices according to the Statistics. During the Advisory Committee, some experts proposed to consider different values of P_{FB} depending on the firemen ability and the intervention time.

Time between Alarm and Action of the FIREMEN	**< 10'**	**< 20'**	**< 30'**	**> 30'**
Type of FIREMEN				
Professional	**0,95** (20)	**0,9** (10)	**0,8** (5)	- (1)
Not-Professional	**0,9** (10)	**0,8** (5)	- (1)	- (1)

Table 6.4: P_{FB} for Office (Reduction N of the fully developed fire probability due to FB)

In case of Automatic fire Detection by Smoke (ADS) and Automatic Alarm Transmission (AAT), the Table 6.4 becomes

Time between Alarm and Action of the FIREMEN	**< 10'**	**< 20'**	**< 30'**	**> 30'**
Type of FIREMEN				
Professional	**0,98** (80)	**0,97** (40)	**0,95** (20)	- (1)
Not-Professional	**0,97** (40)	**0,95** (20)	**0,75** (4)	- (1)

Table 6.5: P_{FB} for Office (Reduction N of the fully developed fire probability due to FB) in case of ADS and AAT.

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Annex A

NFSC - WG 4 Fire Database Questionnaire. For new buildings please fill in 1 to 3, for buildings unfortunately exposed to a fire please fill in 1 to 9.

Example 1

1. Building

- Identification (Building, Street, City, Country)	Kunsttoffrohrwerk, 66, Hütte, 4700, Eupen
- Sketch of building (Floor, Elevation, Situation in town (City map). Type of building (Z, V, G see Fig 1)	G

2. Fire compartment to be evaluated (critical rooms e. g. room of "real fire" outbreak, largest room, room with special hazard as high fire load, concentration of people, rooms on highest floor and lowest floor, below ground level).

Identification: (utilisation of room, location in building)	Extrusion, Injection
length:	First and only floor
width:	l =108 m
height:	b =60 m
floor level: (storey and floor height above /	h =. 5 m
Fire Resistance of structure (< R30, R30, R60, R90, R120)	e = 0 m no:1
Fire Resistance of compartmentation	R ... (R) < 30'
Fire Resistance of slabs	R ... (REI) < 30'
Fire Resistance of facade	R ... (REI) not relevant
Type of structure: combustible/non	R ... (E, RE, REI) 30'
	Steel columns and beams, wooden sheds

3. Occupancy / fire load

Type of occupancy:	Extrusion and injection machines
fire load in compartment:	280 (estimation) MJ/m^2:
Special hazards:	No

4. Safety measures

4.1 Basic measures:

- Portable extinguishers: sufficient/insufficient	Yes Sufficient
- Internal hose ports: sufficient/insufficient	Yes, sufficient
- Type of water supply:	Public system + nearby river
- Amount of water from public network available ≥ 3.600 l/min, ≥ 1.800 l/min, ≥ 900 l/min	Between 900 and 1.800
- Minimal reserved water for fire in public system > 480 m^3, > 240 m^3, > 120 m^3 Distance to nearest hydrant < 70 m, < 100 m, > 100 m	2 small lakes (*étangs*) + river > 480 m^3 < 70 m
- Personal instructed for adequate behaviour in fire situation: available/not available	Yes – Not in the factory at the outbreak of fire

4.2 Special measures:

- Detection
  - Guards(> two rounds per night) — No
  - Automatic detection system (for all building areas/ partial protection) — No
  - Sprinkler system (for all building) —
  - Independent water system for sprinklers — No

- Alarm transmission: —
  - Guard and telephone
  - Guard (min 2 persons 24 hours) and telephone
  - Automatic from detection system to public fire brigade — Manual alarm buttons, transmitted to the guard of the company who is 3 km
  - Automatic from sprinkler to public fire brigade — away from this building.
  - Automatic by special checked and rented safety telephone line to public fire brigade

- Fire brigade
  - Public
    1. ≤ 20 men
    2. ≥ 20 men
    3. ≥ 20 men + extinguishing car with tank
    4. ≥ 20 men + car with tank > 1200 l
    5. As 4. + ≥ 3 men in less then 5 min leaving fire
    6. As 4. + ≥ 5 men in less then 5 min leaving fire
    7. Professional fire brigade — Yes
    8. Large professional fire brigade (big city) with special equipment
  - Time to reach building
    - < 5 km (< 15 min)
    - > 5 km (< 30 min)
    - > 30 min
  - Access to building facade with heavy truck — Yes
  - Work fire brigade
    1. ≥ 10 men during work hours
    2. ≥ 20 men during work hours — Yes
    3. ≥ 20 men all time on workdays + nights
    4. ≥ 20 men all time on + 4 men picket on

5. Evacuation

• Number of people	
- Identification of critical room (name, location in building)	.....
- storey of room with these people	First floor.....
- number of people in this room	20 day and night during week, 0 in the weekend .....
- number of people on this storey	50 during the week days.....
- ability of people (hospitals, prisons, asylums...)	Good (adult workers) .....
- awakeness of people (Hotels, guesthouses...)	Good .....
- normal use (Exposition, schools, shops ...)	Factory .....
- escape route for occupants according to nat. regulations	Yes.....
- rescue route for fire brigade (special / by normal staircase and corridor)	Normal .....

6. Value

• Value at risk:	
- Value of building (at moment of fire)	3 000 000 ECU
- Cost of building (to be rebuilt after fire)	3 000 000 ECU
- Value of building content	17 500 000 ECU
- Number of people in building at outbreak of fire	0.....
- Mean number of people in building (day / night)	/ **20**

7. Loss

• Damage to building	20 500 000 ECU
- Cause of damage (% estimate fire / smoke /	Fire: 90 % / Smoke: 5% / Water: 5%
• Damage to content	8 750 000 ECU
- Cause of damage	Fire, Smoke and Water
• Damage to people	
- killed	.....
- injured	.....

8. Fire

- Time and day (Monday ... Sunday) of fire start	19 Apr. 1998, 00:15, Sunday
- Place of outbreak	Center of the compartment
- Cause of fire (Arson, Electricity ...)	Undetermined, could be electricity

9. Response of fire brigade

- time to give alarm	30 Min
- time: from alarm received to application of water	..... 21 Min
- no. of fire men at site of fire	.....

Example 2

1. Building

- Identification (Building, Street, City, Country)	Hospital, Midhurst, West Sussex, UK ....
- Sketch of building (Floor, Elevation, Situation in town (City map). Type of building (Z, V, G see Fig 1)	3 storeys plus basement..... 250 m x 400 m plan ..... Z – Timber Floor , tiled roof. .....

3. Fire compartment to be evaluated (critical rooms e. g. room of "real fire" outbreak, largest room, room with special hazard as high fire load, concentration of people, rooms on highest floor and lowest floor, below ground level).

	Enclose of origin on ground floor in operating theatre complex (normally secured when not in use)
Identification: (utilisation of room, location in building)	Consultants'rest room
length:	l = ± 5 m.....
width:	b = ± 4 m.....
height:	h = ± 3 m.....
floor level: (storey and floor height above /	e = 0 m ..... no: ground .....
Fire Resistance of structure (< R30, R30, R60, R90, R120)	R ... (R) < 60' (probably : not known) (Masonry).....
Fire Resistance of compartmentation	R ... (REI) < ± 30'.....
Fire Resistance of slabs	R ... (REI) not relevant .....
Fire Resistance of facade	R ... (E, RE, REI) < 30'.....
Type of structure: combustible/non combustible	Part combustible (timber floor, ceiling)
Openings (A_m, h, b, h_{sills})	H = 2-3 m b = 3 m h_{sill} = 0,7 m
Forced ventilation	
Wall (thickness d, type of materials)	Masonry / Block ≅ 150 mm
Roof (thickness d, type of materials)	Timber ≅ 250 mm
Floor (thickness d, type of materials)	Timber ≅ 250 mm (suspended).....

3. Occupancy / fire load

Type of occupancy:	Furniture, electrical equipment
fire load in compartment:	Assessed at 400 MJ/m²
Special hazards:	None.....

4. Safety measures

4.1 Basic measures:

- Portable extinguishers: sufficient/insufficient	sufficient.....
- Internal hose ports: sufficient/insufficient	sufficient.....
- Type of water supply:	.....
- Amount of water from public network available ≥ 3.600 l/min, ≥ 1.800 l/min, ≥ 900 l/min	Public network..... 1.800 l/min .....
- Minimal reserved water for fire in public system > 480 m³, > 240 m³, > 120 m³	..... N/A
Distance to nearest hydrant < 70 m, < 100 m, > 100 m	....
- Personal instructed for adequate behaviour in fire situation: available/not available	Available.....

4.2 Special measures:

• Detection	
- Guards (> two rounds per night) (round every two hours)	Full time staff and control panel for fire /smoke detection system but system being upgraded and existing smoke detector heads were being replaced .....
- Automatic detection system (for all building areas/ partial protection)	None
- Sprinkler system (for all building	N/A .....
- Independent water system for sprinklers	
• Alarm transmission:	
- Guard and telephone	Yes .....
- Guard (min 2 persons 24 hours) and telephone	Yes .....
- Automatic from detection system to public fire brigade	No (relayed by telephone message by Guards / Receptionist) .....
- Automatic from sprinkler to public fire brigade	..... N/A
- Automatic by special checked and rented safety telephone line to public fire brigade	N/A .....
• Fire brigade	
- Public	
1. ≤ 20 men	.....
2. ≥ 20 men	.....
3. ≥ 20 men + extinguishing car with tank	.....
4. ≥ 20 men + car with tank > 1200 l	Available (14 attended incident) .....
5. As 4. + ≥ 3 men in less then 5 min leaving fire	....
6. As 4. + ≥ 5 men in less then 5 min leaving fire	
7. Professional fire brigade	
8. Large professional fire brigade (big city) with special equipment	Yes (12 min alarm to arrival as country district) No ....
- Time to reach building	.....
< 5 km (< 15 min)	.....
> 5 km (< 30 min)	12 mins but ... .
> 30 min	> 5 km .....
- Access to building facade with heavy truck	..... yes .....
- Work fire brigade	.....
1. ≥ 10 men during work hours	.....
2. ≥ 20 men during work hours	N/A
3. ≥ 20 men all time on workdays + nights	N/A
4. ≥ 20 men all time on + 4 men picket on holidays and Sundays	N/A N/A

5. Evacuation

• Number of people	
- Identification of critical room (name, location in building)	Rest room locked at the time..... Ground floor.....
- storey of room with these people	Ground
- number of people in this room	None at time.....
- number of people on this storey	Approx 50 to 160 .....
- ability of people (hospitals, prisons, asylums...)	Some hospital patients
- awakeness of people (Hotels, guesthouses...)	Some sleeping at 0751 .....
- normal use (Exposition, schools, shops ...)	.....
- escape route for occupants according to nat. regulations	Yes
- rescue route for fire brigade (special / by normal staircase and corridor)	Yes, normal staircases, some metal external fire escape stairs

6. Value

• Value at risk:	
- Value of building (at moment of fire)	≅ 10 million ECU
- Cost of building (to be rebuilt after fire)	≅ 50 million ECU
- Value of building content	≅ 10 million ECU
- Number of people in building at outbreak of fire	Not known but > 100.....
- Mean number of people in building (day / night)	Approx 300 / 100

7. Loss

• Damage to building	≅ 250.000 ECU
- Cause of damage (% estimate fire / smoke /	Fire: 50 % / Smoke: 30% / Water: 20%
• Damage to content	≅ 50.000 ECU
- Cause of damage	Fire
• Damage to people	
- killed	No fatalities/injuries .....
- injured	.....

8. Fire

- Time and day (Monday ... Sunday) of fire start	Sunday
- Place of outbreak	Waste bin
- Cause of fire (Arson, Electricity ...)	Careless disposal of cigarette

9. Response of fire brigade

- time to give alarm	Alarm 0749 read 0751
- time: from alarm received to application of water	12 Min
- no. of fire men at site of fire	14 firefighters

V. WORKING GROUP 5

METHODOLOGY TO DEDUCE FROM THE PROBABILITY DATA THE « DESIGN NATURAL FIRE CURVE »

1. INTRODUCTION

The probability that a fire breaks out in a swimming-pool is obviously much lower than in a painting workshop. Moreover the probability that this starting fire spreads and leads to a fully engulfed compartment depends on the compartment area and of course on the active fire fighting measures such as the sprinklers which may extinguish automatically the fire, the firemen or the automatic fire detection (by smoke or heat) and the automatic transmission of the alarm to the firemen which allows a rapid fire brigade intervention.

The WG4 has collected statistics and has deduced the probability that:

- a fire starts (see Tables 5.1 and 6.3 of WG4 report)
- the occupants fail in stopping the fire (see Tables 5.3 and 6.3 of WG4 report)
- the firemen do not succeed in stopping the fire (see Tables 5.3, 6.3 and 6.4 of WG4 report)
- the automatic active measures to extinguish the fire (sprinkler) fail in stopping the fire (see Table 6.2 of WG4 report)

From those probabilities it is possible to deduce γ factors on the fire load by a procedure described in this WG5 report and based on the Annex A of ENV 1991-1[1] and reliability calculations.

This factor has been divided into subcoefficients γ_{q1}, γ_{q2}, γ_{ni} to take into account the compartment size, the building type and the different active fire fighting measures like sprinklers.

The probability of fire start is given per m^2 in WG4 report. The effect of the fire compartment area is considered by the factor γ_{q1} (see Figure 6.3 of this WG5 report). The probability of fire start depends on the occupancy (see Table 6.1 of WG4 report) and has lead to the factor γ_{q2} (see Figure 6.4 of this WG5 report). The failure probabilities of the sprinkler system (from 0,005 to 0,01 in Table 6.2 of WG4 report) and of the firemen (Table 6.3 of WG4 report) imply the γ_{ni} of the Figure 6.5 of this WG5 report.

The characteristic fire load $q_{k,f}$ (see Table 4-3 of the WG3 report) has to be multiplied by $\gamma_{qf} = \gamma_{q1} \times \gamma_{q2} \times \gamma_{ni}$ to obtain the design fire load γ_{df}. The design fire load is then used by the tool developed by WG1 (OZONE) to calculate the design natural fire curve.

The members of the WG5 are the same than the ones of WG4. The Group is led by PA-RE.

Other active measures, which are not covered by statistics of WG4, are also considered by γ_{ni} factors given in Figure 6.6 and deduced by comparison with the effect of other active measures, with other Standards and by discussions with the experts of the Advisory Committee.

2. INFLUENCE OF THE ACTIVE FIRE FIGHTING MEASURES

2.1 INTRODUCTION

Many methods of Fire Safety Engineering have pointed out the influence of the Active fire fighting measures:

- DIN 18230 "Baulicher Brandschutz im Industriebau" for Germany [2, 3, 4, 5]
- The Austrian Standards TRVB A126 et TRVB A100 "Brandschutztechnische Kennzahlen verschiedener Nutzungen, Lagerungen, Lagergüter" and "Brandschutzeinrichtungen rechnerischer Nachweis" [6]
- Fire Engineering Design for Structural Stability in New-Zealand [7]
- SIA 81 "Evaluation du risque d'incendie" for Switzerland [8]
- FRAME for Belgium [9]

Moreover it is obvious that people sleep safer in a hotel with smoke detectors and sprinklers with a structural fire resistance of R30 than in a R90 building without any active protection measures. Nevertheless only one sentence can be found in Annex D of ENV 1991-2-2 about this major factor [1].

2.2 ANNEX D OF ENV 1991-2-2 [1]

EC 1 part 2-2 [1] considers the influence of active fire protection measures by the differentiation factor γ_n in Annex D. It is used in the scope of equation (D.1) determining the design fire load q_d.

$$q_d = \gamma_q \cdot \gamma_n \cdot q_k \qquad (D.1)$$

The characteristic value of the fire load q_k has to be multiplied by the global safety factor γ_q for the accepted failure risk in connection with the expected fire occurrence probability. The multiplication with γ_n finally leads to the design fire load.
Annex D of EC 1 does not contain much information about numerical values of γ_n. Beside the advice to fix γ_n to 0,6 for approved fire extinguishing systems the Eurocode only refers to national regulations.

2.3 DIN 18230 "BAULICHER BRANDSCHUTZ IM INDUSTRIEBAU"[2, 4, 5]

2.3.1 GENERAL DESCRIPTION OF DIN 18230

In connection with the German Industriebaurichtlinie, DIN 18230 offers a calculation method to determine the requested fire resistance time of a compartment. The application of this standard which generally takes active and passive fire safety measures into account is restricted to industrial buildings with a limited floor area of 30.000 m^2 [3]. Buildings which are not involved in industrial production or storage, e.g. skyscrapers, silos and power plants are excluded.

The first step in DIN 18230 is to calculate the fire load q_R by the following equation (2.1). It mainly depends on the combustibility of the component parts and the stored material in the compartment. Beiblatt 1 to DIN 18230 contains a summary of the combustion factor m and the calorific value H_u for commonly used materials. q_R is generally referred to the floor area A_f of the compartment.

$$q_R = \frac{\sum(M_i . H_{ui} . m_i . \psi_i)}{A_f} \qquad (2.1)$$

The equivalent time t_a is calculated by the following equation:

$$t_a = q_R \, . \, c \, . \, w \qquad (2.2)$$

The transformation factor c considers the heat transfer through the fire compartment enclosure. It is equal to the conversion factor k_b in Table E.1 of EC 1 part 2-2 Annex E [1]. The numerical values differ between 0,04 $\frac{min.m^2}{MJ}$ and 0,07 $\frac{min.m^2}{MJ}$ resp. between 0,15 to 0,25 $\frac{min.m^2}{kWh}$ in the German code, in relation to the thermal properties of the enclosure walls, ceilings and floor.

The ventilation factor w in equation (2.2) considers the ventilation conditions in the compartment. For its determination DIN V 18230 (sept. 1987) [2] defines the estimated opening area A_{v+h} which has to be calculated by adding the vertical opening area A_v to the horizontal opening area A_h multiplied by a dimensionless factor k_f ($\Rightarrow$ DIN V 18230 (sept. 1987) [2] diagram 1).

$$A_{v+h} = A_v + k_f \, . \, A_h$$

The ratio of the estimated opening area A_{v+h} to the floor area A_f of the compartment is required for Table 2.1 of the standard leading to the ventilation factor w. This table differentiates between the position of the openings.

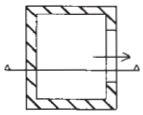
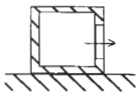
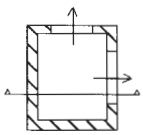
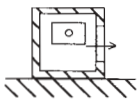
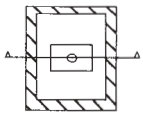
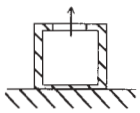
Openings Position	Ground Plan	Section	A_{v+h} / A_f to 0,05	>0,05 to 0,10	>0,10 to 0,15	>0,15 to 0,20	>0,20 to 0,25	>0,25
Compartment with openings on only one side			3,2	2,0	1,5	1,2	1,0	0,9
Compartment with openings on at least two sides			2,2	1,5	1,0	0,9	0,7	0,6
Compartment with horizon-tal opening			1,8	1,2	0,9	0,7	0,6	0,5

Table 2.1: Table 3 of DIN 18230 (sept. 1987) [6] for the ventilation factor w

Finally the required fire resistance time erf t_F can be calculated:
erf $t_F = t_a \cdot \gamma \cdot \gamma_{nb}$

γ is a global safety factor which depends on the compartment size and the relevant fire safety class SK_b 1 - 3. The fire safety class corresponds to the required safety level of each component part, e.g. dividing walls and load bearing elements are generally classified into class SK_b 3 (high requirements). For instance, for a column in a multi-storey building of 2500 m^2, γ is equal to 1,25.

γ_{nb} considers the influence of active fire safety measures like sprinkler systems or work fire brigades, e.g. if an automatic sprinkler system is provided, γ_{nb} gets to 0,6.

Other values for γ_{nb} can be taken from the following table which is the translation of the table 6 of DIN V 18230 (sept. 1987) [2].

work fire brigade number of firemen	sprinkler system	no sprinkler system
0	0,6	1,0
1 team	0,55	0,9
2 teams	0,5	0,8
3 teams	0,4	0,7
4 teams	0,35	0,6

Table 2.2 : Additional factor γ_{nb} according to DIN V 18230 (sept. 1987)

After its calculation the required fire resistance time has to be related to the corresponding fire resistance class R.

$0 < \text{erf } t_F \leq 15 \text{ min} \rightarrow$ no fire protection
$15 < \text{erf } t_F \leq 30 \text{ min} \rightarrow$ R 30
$30 < \text{erf } t_F \leq 60 \text{ min} \rightarrow$ R 60
$60 < \text{erf } t_F \leq 90 \text{ min} \rightarrow$ R 90
$90 < \text{erf } t_F \leq 120 \text{ min} \rightarrow$ R 120

DIN 18230 only determines the required fire resistance time for a compartment. The verification and the design of each component part have to be done according to DIN 4102 part 4 [10].

2.3.2 DRAFT ON DIN 18230 (JULY 1994 AND SEPTEMBER 1995) [4, 5]

In comparison to the prestandard of 1987 the draft editions of DIN 18230 from 1994 [4] and 1995 [5] do not contain substantial differences concerning the general calculation method of the equivalent fire resistance time. The determination of the ventilation factor w has been revised. The estimated opening area A_{v+h} has been replaced by the partial factors a_w and w_0. The factor a_w takes the height of the compartment into account, while w_0 depends on the ratios of the vertical and horizontal openings to the floor area. Diagrams determine both factors. Finally the ventilation factor can be calculated by a simple multiplication:

$$w = w_0 \cdot a_w$$

The values of the global safety factors have been modified slightly.
The following table contains the values of the additional factor for the influence of active fire safety measures. **The symbol for this factor has been changed from γ_{nb} to a_L.** The application has been enlarged to non-professional work fire brigades, detectors and manual sprinkler systems.

(1)			(2)	(3)	
work fire brigade					
number of firemen	professional	non-professional	detectors	manual fire extinguishing systems	automatic sprinkler systems
0	1,0	1,0	0,9	0,85	0,6
1 team	0,9	0,95			
2 teams	0,8	0,85			
3 teams	0,7	0,8			
4 teams	0,6	0,75			

Table 2.3: Additional factor a_L - DIN 18230 (september 1995) [5]

The final value of a_L is made up of a multiplication of column (1), (2) and (3).

2.4 AUSTRIAN STANDARDS TRVB A126 AND TRVB A100 [6]

The basic concept of the Austrian standard TRVB is similar to the Swiss one used in SIA [8]. The specific fire risk B is determined according to the main equation in accordance with the individual factors as fire load Q, fire danger C, smoke danger R etc., which are given as table values.

$$B = Q.\ C.\ R.\ K.\ P.\ E.\ H$$

The characteristic risk number SF is depending upon the fire risk B and the measures of smoke exhausting.

$$SF = (G + K_1) \cdot B/K_2$$

The presence or absence of a sprinkler system is not taken into account in the formula above.

The necessary active fire protection measures according to the fire resistance duration of the structural components are determined in accordance with the characteristic risk number SF. Hereby, the possibility of changing fire protection measures exists. For example, for the calculated characteristic risk number SF 3.0, both following solutions are allowed, the fire resistance class R60 with a fire alarm system or unprotected steel structures with a sprinkler system (in both cases a work fire brigade has to exist).

2.5 NEW-ZEALAND METHOD [7]

The chapter "Fire Engineering Design for Structural Stability" of [7] provides the following formula:

$$S_c = c_1 \cdot c_2 \cdot c_3 \cdot c_4 \cdot \omega \cdot q_f$$

where:

S_c = calculated security rating (minutes)
c_1 = enclosure (firecell) surface thermal coefficient
= 0,067 for typical applications
c_2 = structural element ductility or compression gravity loading factor
c_3 = 1,0 for unsprinklered firecells
= 0,6 for sprinklered firecells
c_4 = ventilation configuration coefficient
= 1,0 for satisfactory ventilation configuration when $A_v > 0{,}03\ A_{df}$
= 1,25 for unsatisfactory ventilation configuration when $A_v > 0{,}03\ A_{df}$
= 1,0 for any ventilation configuration when $A_v \leq 0{,}03\ A_{df}$
ω = ventilation factor
q_f = design fire load energy density/m^2 floor area (FLED)

The ventilation factor, ω, is given by:

$$\omega = \frac{A_{df}}{A_{dt}(A_v\sqrt{h_v} / A_{dt.})^{0.5}}$$

where:

A_{df} = design fire area = lesser of A_f or 150 m^2
A_f = firecell floor area
A_v = ventilation area considered accessed by the fire
h_v = weighted mean height of openings A_v
A_{dt} = total surface area occupied by the area of design fire

As in ENV 1991-2-2 [1], the sprinklers are considered by multiplying the fire load by a factor 0,6. The reduction is based on a paper of Malhotra [11].

2.6 FIRE RISK EVALUATION ACCORDING TO SIA DOC. 81 [8]

2.6.1 DESCRIPTION OF THE METHOD

In 1960 Dipl. Ing. ETH Max Gretener, head of the Brand-Verhütungs-Dienst BVD (Swiss Fire Protection Association) in Zurich, started to study possibilities to calculate the fire risk in industrial premises and other large buildings. He developed an easy tool to use risk assessment method which was first published in 1965 and focused on the needs of the fire insurance companies. In 1968 it was proposed to use the method also to set the fire protection measures by the fire police.

In 1984 the Fire Risk Evaluation Method SIA Documentation 81 was published. It was derived from the work of Max Gretener. The method was completely revised by a project team consisting of members from the VKF (association of monopolistic state insurance companies) the BVD (representing also the private fire insurance companies) and the Swiss Association of Engineers and Architects SIA. This project team adapted the method to new national and international knowledge and experience. Emphasis was given to make the method easy to use by fire police, insurance people, engineers and architects.

The method is well accepted in Switzerland and even recommended in the fire regulation as a tool to evaluate and compare the fire risk of alternative concepts (trade-off between sprinkler and detection and passive fire protection).

Below a short description of the method is given:
It is a method based on a large statistical survey on fire loads and on building losses. It consists in the verification of a global fire safety factor γ_{Fire}:

$$\gamma_{Fire} = \mathbf{R}_{accepted} / \mathbf{R}_{calculated} \geq \mathbf{1}$$

It is a check to verify that the calculated risk of given compartment is smaller than the accepted risk.

$R_{accepted}$ is a function of the number and the mobility of the persons involved and of the location of the relevant fire compartment within the building.

$R_{calculated} = A \times B$ A representing the probability of occurrence of a fire
B representing the probable amount of losses

$$B = P_{danger} / M_{applied}$$

P_{danger} is a function of the following parameters:

* fire load density and distribution
* combustibility of the fire loads
* smoke production
* production of corrosive agents
* combustibility of the building components
* area of the compartment or building
* storey of the compartment to be checked/height of the building

$M_{applied}$ is a function of:

* basic normal measures which includes the:
  - quality and number of internal fire fighting devices such as portable fire extinguisher and internal hydrants
  - reliability and quality of water supply
  - distance to nearest hydrants
  - quality of staff instruction in case of fire

* active measures which includes the:
  - type of fire detection devices and measures
  - reliability and rapidity of alarm transmission
  - reliability, rapidity and quality of fire brigades
  - type of fire suppression devices
  - presence of smoke and heat extraction devices

* passive, structural measures which includes the:
  - level of structural fire resistance
  - the type of the facade used as a barrier against the spread of fire
  - the fire resistance level of compartmentation
  - the ventilation characteristics of the fire compartment

With regard to questions of validity, the Swiss Fire Risk Assessment method has the advantage of not just claiming to have a purely scientifical background, but to be an empiricalistic procedure tested by a wide practical application. However it is based on a large background statistical data, and a scientific validation for this method could certainly be developed if needed.

2.6.2 INFLUENCE OF ACTIVE MEASURES

The SIA-method grades the influence of active measures on the global fire risk. With regard to sprinklers the following parameters are taken into account:

- detection (sprinklers activate an alarm bell if water is flowing through the main valve)
- alarm transmission (the sprinkler alarm is often - in Switzerland mandatory - connected directly to the fire brigade)
- suppression function (water discharge on fire)

The method proposes the following risk reduction factors:

– detection (parameter S_{13}) : $S_{13} = 1,20$

– alarm transmission by specially protected telephone lines (parameter S_{24}) : $S_{24} = 1,20$

– suppression function : $S_{51} = 1,7$

or for annually checked sprinkler system designed according to regulations (*) : $S_{51} = 2,0$ (*)

The global risk reduction factor $\gamma_n = 1/(\Sigma s_i)$ is found to be:

- Sprinkler without automatic alarm to fire brigade:

$$\gamma_{n1} = \frac{1}{S_{13} \cdot S_{51}} = \mathbf{0,49} \text{ (or 0,42 see*)}$$

- Sprinkler with automatic alarm to fire brigade:

$$\gamma_{n2} = \frac{1}{S_{13} \cdot S_{24} \cdot S_{51}} = \mathbf{0,41} \text{ (or 0,35 see*)}$$

These values are lower than the value for the reduction of the design fire load in Annex D of ENV1991-2-2 [1]. $\gamma_n = [0,6]$.

While Annex D mainly considers the suppression function (reduction of fire load), the SIA method also considers alarm and alarm transmission (e.g. earlier evacuation and fire brigade action). This may explain the better rating of sprinkler systems within the SIA method. This better rating is supported by the insurance companies who apply premium reductions up to 60 % and more for sprinkler systems. This could lead to the assumption that their risk assessment systems also come to the conclusion of a risk reduction of roughly 60 % e.g. $\gamma_n = (1-0,6) = 0,4$.

2.7 METHOD FRAME [9]

The method FRAME for Fire Risk Assessment Method for Engineering made by Mr. E. De Smet and published by ANPI (Association Nationale pour la Protection Incendie) in Belgium is based on the Swiss SIA 81. This method FRAME enable one to calculate two risks in case of fire, the risk for the contents and the risk for the people.

In the case of the risk of the contents, the sprinklers have an influence on the detection and on the fire extinction.

The risk reduction factor is 1,22 for the detection which can be considered only if there is a connection to the fire brigade. Concerning the fire suppression function, the risk is again reduced by a factor equal to 1,71 for sprinklers without independent water source, to 1,98 for sprinklers with one independent water source and to 2,65 for sprinklers with two independent water sources. This last case leads to a value of γ_n equal to $1/(2,65 \cdot 1,22) = 0,31$.

In the case of the risk for the people, the fire risk reduction factor is the same for the detection. But the sprinklers also play a part in the protection of the evacuation.
The reduction factor is 1,27 if there are sprinklers only in high risk areas and is equal to 1,63 if there are sprinklers in the whole building.

2.8 CONCLUSION

The following table enables one to compare the Annex D of ENV 1991-2-2 [1] to the other methods (it has to be underlined that the reduction is not applied directly to the fire loads for the last three methods [7,8,9] and of course for the insurance premium reduction).

Method	Sprinkler effect (Detection and extinction): γ_n
ENV 1991-2-2 [1]	0,6
DIN 18230 [2, 3, 4, 5]	0,54 (= 0,6 x 0,9)
New Zealand [7]	0,6
SIA 81 [8]	0,35 to 0,49
FRAME [9]	0,31 to 0,48
Insurance Companies	Premium reduction: Initial premium multiplied by up to 0,4

Table 2.4

The value 0,6 of γ_n in Annex D of ENV 1991-2-2 appears high and should be divided into sub-coefficients taking into account the sprinkler types, the water supply, the detection and the communication of the alarm to the fire brigade.

3. DEVELOPMENT OF THE NEW METHODOLOGY BASED ON ANNEX A OF ENV1991-1

3.1 INTRODUCTION

The probability that a fire breaks out in a swimming-pool is obviously much lower than in a painting workshop. Moreover the probability that this starting fire spreads and leads to a fully engulfed compartment depends of course of the active fire fighting measures such as the sprinklers which may extinguish automatically the fire, the firemen or the automatic fire detection (by smoke or heat) and the automatic transmission of the alarm to the firemen which allows a rapid fire brigade intervention.

Concerning the influence of the sprinklers, some surveys, some tests and numerical simulations attest that there is no risk for the stability of the structure if the sprinkler system has been well designed and works when a fire breaks out. The influence of the sprinklers on the structure behaviour is thus only a question of reliability. Will the sprinklers work when necessary ? In order to quantify the influence of the active measures, the approach described in ENV 1991-1 [24] has been used. The Eurocode 1 Part 1-1 [24] concerning the design values of the actions and the resistances is based on a probabilistic concept that has lead to safety coefficients γ ,so that this concept can be applied in practice. The safety factors γ for the actions and the material properties has been deduced by a semi-probabilistic approach (Annex A of ENV 1991-1 [24]) which assumes implicitly that the failure probability of the structure p_f is lower than a target failure probability of 7,25E-5 per working life of the building, which is equivalent to a safety factor β of 3,8 :

$$p_f \text{ (failure probability)} \leq p_t \text{ (target probability)} \quad (1).$$

In case of fire, the main action is the fire which can be quantified by the fire load expressed in kg of wood or in MJ. However, this fire load becomes a real action for the structure only when there is a fire. The fire load influences really the structure only with a certain probability p_{acc}, p_{acc} being the product of p_1 (probability that a fire starts) and p_2 (probability that this starting fire turns to a flash-over or a fully engulfed fire compartment).

In case of fire which is considered as an accidental action [1] the equation (1) becomes p_f (failure probability in case of fire) * p_{acc} (probability of fire) $\leq p_t$ (target probability). In that way the safety index β_{fi} has to be determined by using $p_{t,fi}$ which is equal to (p_t /p_{acc}) and enables us to determine the corresponding safety factor γ_{qf} for the fire load.

3.2 DETERMINATION OF THE DESIGN VALUES AND SAFETY FACTOR γ IN THE EUROCODES - PRINCIPLE

The resistance R and the Action S are according to statistical distributions which are defined by the standard deviation and the mean. To ensure a sufficient safety, it is necessary that the failure (S > R) occurs only with a very low probability given by the hatched area (see Figure 3.1). This area can be measured by the safety index β.

The Eurocode gives a failure probability of $7{,}25.10^{-5}$ for the building life, which corresponds to a safety index β of 3,8.

However, there are a lot of actions: (self weight, variable load, snow, wind, earthquake, fire..) and a lot of resistances (compressive strength of concrete, yield point of the steel of the profiles, rebars, bending resistance, buckling resistance...)

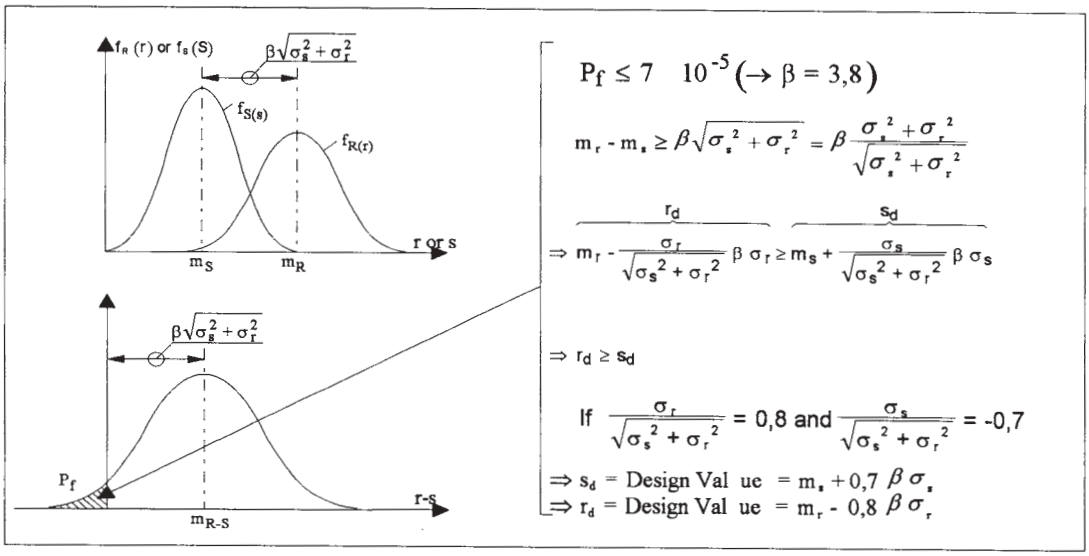


Figure 3.1

Therefore the problem is much more complex than the comparison between two statistical variables. That's why the Eurocodes have adopted a semi-probabilistic approach based on the FORM method (First Order Reliability Method).

This simplification of the Eurocodes consists of assuming:

$$\alpha_R = \frac{\sigma_R}{\sqrt{\sigma_R^2+\sigma_S^2}} = 0{,}8 \text{ for the resistance.}$$

$$\alpha_S = \frac{\sigma_S}{\sqrt{\sigma_R^2+\sigma_S^2}} = (-0{,}7) \text{ for the main action and } (-0{,}28) \text{ for the secondary action}$$

By considering constant values for the weighing factors α_{si}, the design values s_d for actions can be defined without referring to the resistance, as these design values depends only on the safety index β, on the standard deviation of the statistical

distribution of the action and, of course, on the type of the distribution (see table A3 and equations A.3a, A.3b, A.4.a and A.4.b of ENV 1991-1 [24]).

This design value s_d of one action is thus the value of the action which has to be considered in order to obtain the required safety. If β is equal to 3,8 as in the Eurocode, this implies that the failure risk is equal to $7{,}25.10^{-5}$ during the building life.

As a consequence, for each action, it is possible to define safety coefficient γ which is the ratio between the design value s_d and the characteristic value, which is the usual reference value :

$$\gamma = \frac{s_d}{s_k}$$

In this way we can find the safety coefficients given in the Eurocodes : on the action side 1,35 and 1,5 for the self weight and the imposed loads; on the resistance side 1,1 , 1,15 and 1,5 for respectively structural steel, reinforcement bars and concrete.

3.2.1 SELF WEIGHT [24, 29(CHAPTER 9), 30]

- $\beta = 3{,}8$; $\alpha = -0{,}7$
- Statistical law : Gaussian
- Variation coefficient $V_G = \frac{\sigma_G}{m_G} = 0{,}1$

  with σ_G the standard deviation and
  m_G the mean
- γ_{sd} : safety factor for the model for calculating the action effects = 1,05.
- Design value : $G_d = \gamma_{sD} (m_G - \alpha \beta \sigma_G)$

$$= 1{,}05\ m_G\ (1 + 0{,}7 . 3{,}8 . V_G)$$
$$= 1{,}05\ m_G\ (1 + 0{,}7 . 3{,}8 . 0{,}1)$$
$$= 1{,}33\ m_G$$

- Characteristic value G_k : it is normally taken from the nominal values of the dimensions and the density. Hence G_k is the mean value :

$$G_k = m_G$$

- Safety factor : $\gamma_G = \frac{G_d}{G_k} = \frac{1{,}33\ m_G}{m_G} = 1{,}33$

3.2.2 VARIABLE LOADS [24, 29(CHAPTER 9), 30]

- $\beta = 3,8$; $\alpha = -0,7$
- Statistical law : Gumbel type I
- Variation coefficient $V_Q = \dfrac{\sigma_Q}{m_Q} = 0,3$

  with σ_G the standard deviation and
  m_G the mean
- γ_{sd} : safety factor for the model for calculating the action effects = 1,05.
- Design value : $$Q_d = \gamma_{sD} \left\{ u - a^{-1} \ln[-\ln \phi(-\alpha \beta)] \right\}$$

  with $$u = m_Q - \frac{0,577}{a} ;$$

  ϕ, the distribution function of the normal distribution

  and $$a = \frac{\pi}{(\sigma_Q \sqrt{6})}$$

$$Q_d = 1,05\ m_Q \left\{ 1 - \frac{\sqrt{6}}{\pi} V_Q \left(0,577 + \ln\left[-\ln \phi\ (-\alpha \beta)\right]\right) \right\}$$

$$Q_d = 1,05\ m_Q \left\{ 1 - \frac{\sqrt{6}}{\pi} V_Q \left(0,577 + \ln\left[-\ln \phi\ (0,7 \beta)\right]\right) \right\}$$

- Characteristic value Q_k corresponding to the 95 % fractile value

$$Q_k = m_Q \left\{ 1 - \frac{\sqrt{6}}{\pi} V_Q \left(0,577 + \ln\left[-\ln\ (0,95)\right]\right) \right\}$$

- Safety factor :

$$\gamma_Q = \frac{Q_d}{Q_k} = 1,05 \frac{\left\{ 1 - \frac{\sqrt{6}}{\pi} V_Q \left(0,577 + \ln\left[-\ln \phi\ (0,7 \beta)\right]\right) \right\}}{\left\{ 1 - \frac{\sqrt{6}}{\pi} V_Q \left(0,577 + \ln\left[-\ln\ (0,95)\right]\right) \right\}} = 1,46$$

3.2.3 STRUCTURAL STEEL [24, 30]

- $\beta = 3,8$; $\alpha = 0,8$
- Statistical law : Lognormal
- Variation coefficients :

V_R = coefficient of variation for the Design Value = $\sqrt{V_G^2 + V_m^2 + V_f^2} = 0,052$
V_m = coefficient of variation for Model uncertainly = 0,03
V_G = coefficient of variation for Geometry of element = 0,03
V_f = coefficient of variation for property = 0,03

- Design value : $X_d = m_X \exp(-\alpha_R \beta V_R)$
$= m_X \exp(-0,8 \beta V_R)$
- Characteristic value : $X_k = m_X \exp(-k V_f)$
with k = 1,645 corresponding to the 5 % fractile
- Safety Factor : $\gamma_a = \frac{X_k}{X_d} = \exp(0,8 \beta V_R - k V_f)$
$= \exp(0,8 \cdot 3,8 \cdot 0,052 - 1,645 \cdot 0,03)$
$= 1,11$

3.2.4 FIRE LOAD [24, 30]

The fire load may also be considered as an action. However this action is an accidental action so that the target value in case of fire $p_{t,fi}$ is equal to the ratio of p_t , the target value probability and p_{acc} , the probability that the accidental action occurs :

$$p_{t,fi} = \frac{p_t}{p_{acc}}$$ (see chapter 4.2.4 of [29])

- In that way, the safety index β_{fi} is no more the fixed value 3,8 but depends on the different factor influencing p_{acc} (building occupancy types, fire compartment area, active fire fighting measures) : $\beta_{fi} = f(p_{t,fi})$
- Assuming that the fire load is the main action in case of fire, the weighing factor α for the fire load is -0,7 : $\alpha_{qf} = -0,7$. Chapter 4 points out that this assumption should be modified ($\alpha_{qf} = -0,9$). Moreover that calculation shows that the weighing factor for the main action at room temperature is strongly reduced in case of fire and may therefore considered as a secondary action.
- Statistical law : Gumbel type I.

According to the fire load densities given in the U.K. document "The Application of Fire Safety Engineering Principles to the Safety in Buildings" [5] and Prof. Fontana's analyse [20] and [22], the data of fire loads fit well into a Gumbel type I distribution. That's why the Gumbel distribution will be used in this paper. However the procedure of this paper could be easily applied with another statistical law (lognormal ...).

- $\gamma_{sD} = 1{,}05$
- Variation Coefficient : $V_{qf} = 0{,}25$ [5]
- Design Value (see variable loads) :

$$q_{f,d} = 1{,}05\, m_{qf} \left\{1 - \frac{\sqrt{6}}{\pi} V_{qf} \left[0{,}577 + \ln\left(-\ln \phi(-0{,}7\,\beta)\right)\right]\right\}$$

- Characteristic value $q_{f,d}$ corresponding to 80 % fractile (see Annex D of ENV 1991-1-2 [1]) or 90 % fractile (see DIN 18230 [5]). The 80 % fractile value has been considered in the following pages.
- Safety Factor

$$\gamma_{qf} = \frac{q_{f,d}}{q_{f,k}} = 1{,}05 \frac{\left\{1 - \frac{\sqrt{6}}{\pi} V_{qf}\left[0{,}577 + \ln\left(-\ln \phi(-0{,}7\,\beta)\right)\right]\right\}}{\left\{1 - \frac{\sqrt{6}}{\pi} V_{qf}\left[0{,}577 + \ln\left(-\ln 0{,}8\right)\right]\right\}}$$

$$= 1{,}75 \text{ for } \beta = 3{,}8$$

The evolution of γ_{qf} as a function of β is given by the Figure 3.2.

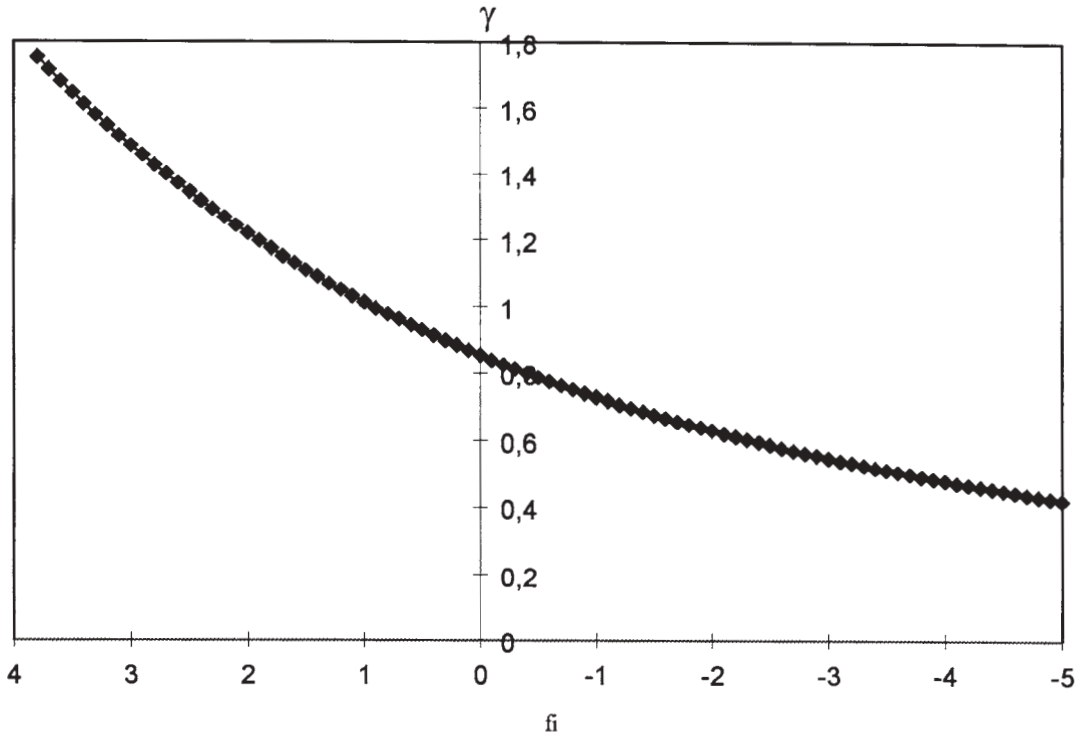


Figure 3.2 : Safety factor γ_{qf} as a function of β

Knowing the probability of a general fire (Fully Engulfed fire Compartment) depending on the fire compartment size, the type of occupancy and the active fire fighting measures, the safety index β_{fi} depending on the target failure value p_t divided by the probability of a general fire, p_{acc} can be deduced.

$$\beta_{fi} = \phi^{-1}\left(\frac{p_t}{p_{acc}}\right) = \phi^{-1}\left(\frac{7{,}25 \cdot 10^{-5}}{p_{acc}}\right)$$

The Figure 3.2 enables then to deduce the factor γ_{qf} for the fire load.

However this global procedure implies the calculation of the fire probability for each case. That's why we have proposed a simplified approach which consists of splitting the safety factor $\gamma_{fire\ load}$ into 3 coefficients γ_{q1} to consider the compartment size, γ_{q2} to consider the risk of fire activation and γ_{ni} to take into account the influence of the active measures.

3.3 DETERMINATION OF THE DIFFERENTIATION FACTORS γ_{Q1}, γ_{Q2} AND γ_{QN}

3.3.1 REFERENCE CASE

According to the background of the DIN 18230 [5], the probability to have a fully engulfed compartment per m^2 per year in the schools, hotels or offices is equal to $5 \cdot 10^{-7}$. This probability can be divided into p_1, probability that the fire starts and p_2, probability that this starting fire turns to a flash-over.

By multiplying by 50, we obtain the probability for the complete life of the building estimated to 50 years : probability of a compartment fully engulfed by the fire :

$$p_1 p_2 = 5 \cdot 10^{-7} \cdot 50 = 25 \cdot 10^{-6}$$

If we consider a fire compartment of 25 m^2 (A_f), the probability p_{acc} of a fully engulfed fire compartment is :

$$p_{acc} = p_1 p_2 A_f = 6{,}25 \cdot 10^{-4}$$

The target value of the failure becomes then :

$\frac{p_t}{p_{acc}} = \frac{7{,}25 \cdot 10^{-5}}{6{,}25 \cdot 10^{-4}} = 0{,}116$ and the corresponding safety index β_{fi} is equal to 1,2.

This factor β_{fi} of 1,2 implies a safety factor γ of 1,0 in case of 80 % fractile for the characteristic fire load. This safety factor corresponding to the reference case will be noted γ_{ref}.

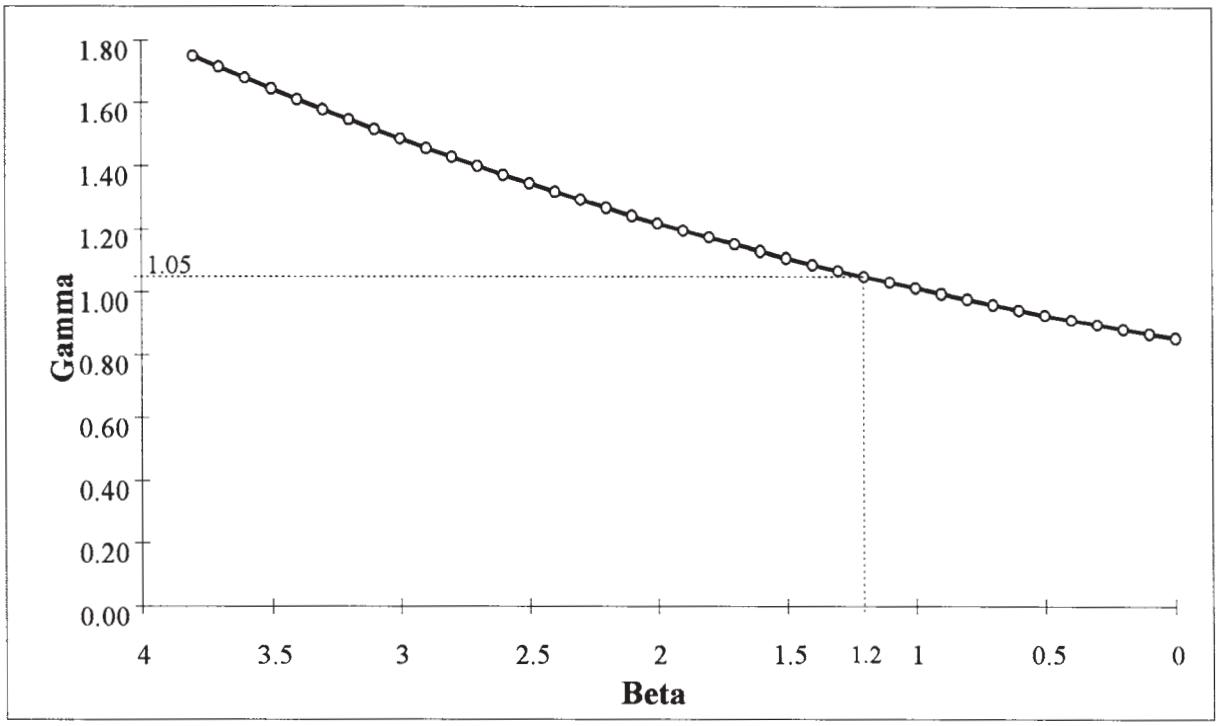


Figure 3.3 : Safety Factor γ on the Fire Load corresponding to a characteristic value of 80% fractile.

3.3.2 DIFFERENTIATION FACTOR γ_{Q1} - INFLUENCE OF THE COMPARTMENT AREA

In the same way, we can obtain other safety coefficients γ for other areas A_f.

A_f [m^2]	λ_b	P_t / λ_b	β_{fi}	γ	$\gamma_{q1} = \gamma/\gamma_{ref}$
25	$6{,}25 \cdot 10^{-4}$	0,11600	1,22	1,0	1,0
250	$6{,}25 \cdot 10^{-3}$	0,01160	2,28	1,25	1,25
2500	$6{,}25 \cdot 10^{-2}$	0,00116	3,03	1,5	1,5
5000	$12{,}5 \cdot 10^{-2}$	0,00052	3,26	1,6	1,6
10000	$25 \cdot 10^{-2}$	0,00029	3,45	1,65	1,65

Table 3.1

Let's call γ_{q1} the factor γ divided by the safety factor of the reference γ_{ref}.

3.3.3 DIFFERENTIATION FACTOR γ_{Q2} - INFLUENCE OF THE RISK OF FIRE ACTIVATION

The previous calculation is based on a probability of fire p_1 p_2 of 5.10^{-7} per year and m^2.

This value corresponds to schools, offices or hotels. It is obvious that the risk is much higher for a fireworks industry and lower for a museum with Grecian statues.

For a building of 2500 m^2, the safety coefficient γ is equal to 1,5 [see Table 3.1]. What happens if the probability of having a fire is reduced by 10 ? The Figure 3.4 shows that the safety coefficient γ is reduced by a factor 0,85.

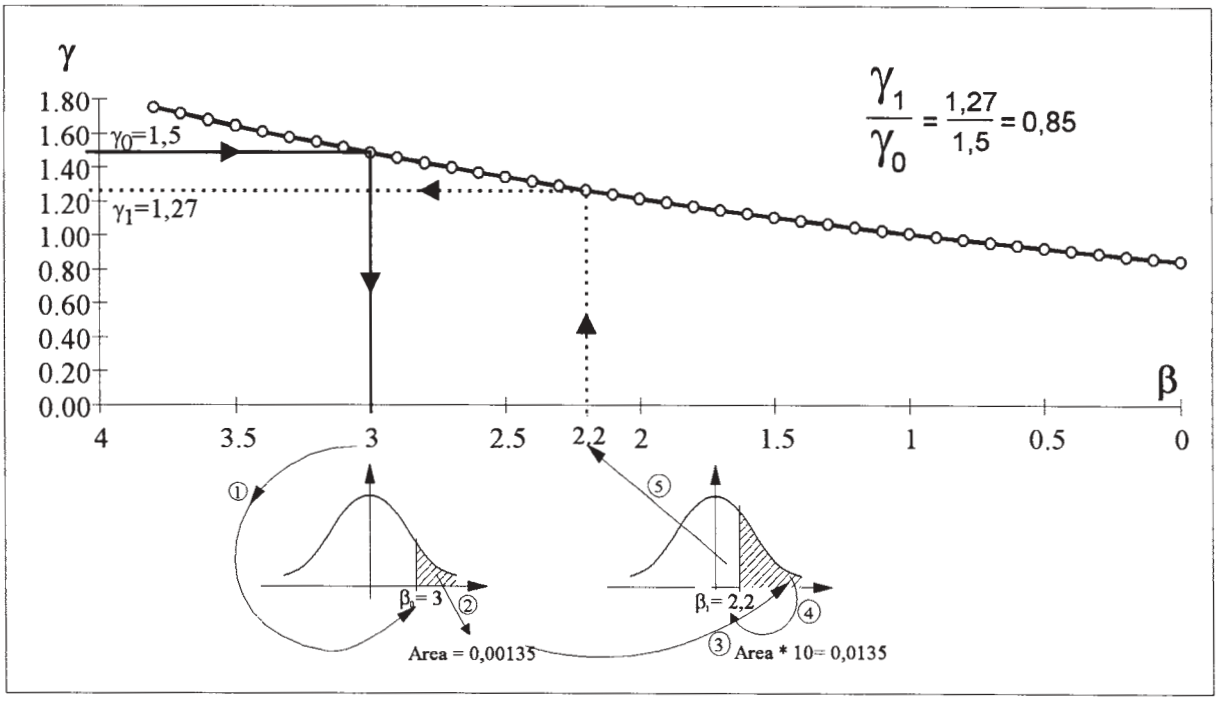


Figure 3.4

Moreover, the Figure 3.5 shows that this factor 0,85 doesn't change a lot if we make a variation on the starting point β_0.

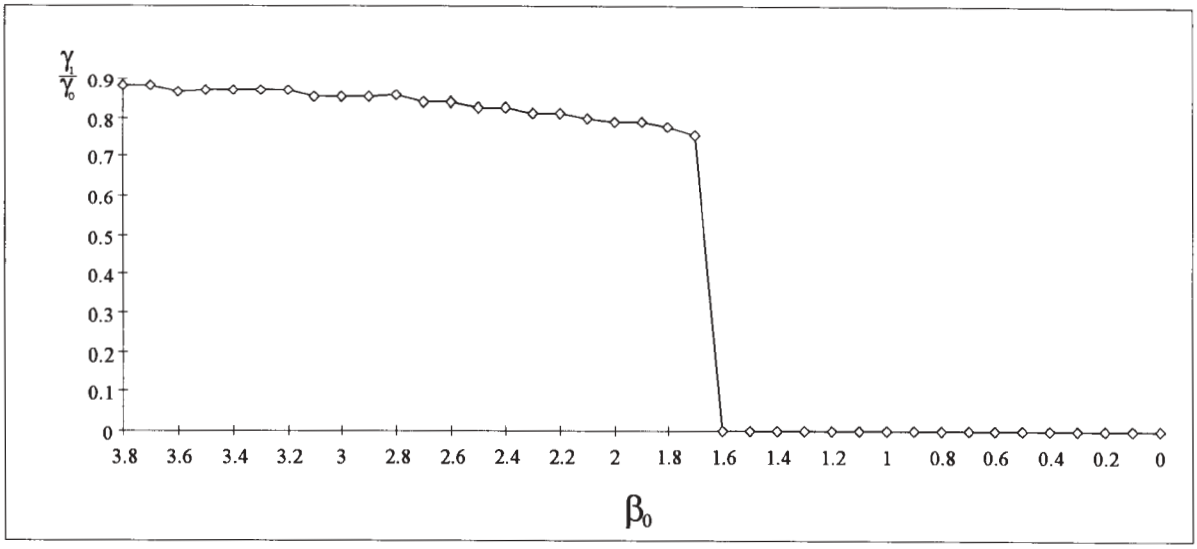


Figure 3.5

In this way, the buildings can be classified according to the danger of fire activation. For instance, the category 2 (Hotel, School, Office) has a danger of fire activation 10 times higher than the category 1 (Museum, Art Gallery) and 10 times lower than the category 3 (Engine Fabrication). For each class, it is possible to deduce an additional safety coefficient γ_{q2} which has to multiply the coefficient γ_{ref} and the factor γ_{q1} of the previous table.

Type of building Destination	Danger of fire activation	$N = \frac{(p_{acc})}{(p_{acc,ref})}$	$\gamma_{q2} = \frac{\gamma}{\gamma_{ref}}$
Museum, Art gallery	Low	10^{-1}	0,85
Hotel, School, Office	Normal	1	1
Engine Fabrication	Average	10	1,2 ($\cong$ 1 / 0,85)
Painting Workshop Chemistry Laboratory	High	100	1,4 ($\cong$ 1 / 0,85²)
Painting Fabrication Fireworks Industry	Higher	1000	1,6 ($\cong$ 1 / 0,85³)

Table 3.2

3.3.4 DIFFERENTIATION FACTOR γ_N - INFLUENCE OF THE ACTIVE FIRE FIGHTING MEASURES

In the same way, the influence of active fire fighting measures can be quantified. Each active measure reduces the probability p_{acc} that a starting fire turns to a flash-over or a fully engulfment of the compartment by a factor N. Therefore, for each active measure it is possible to deduce a coefficient γ_n smaller than 1 to take into account the sprinklers, the firemen or the detection measures.

The Figure 3.6 is similar to the Figure 3.5 but other fire probability reductions N have been considered.

The Figure 3.6 attests that the factors γ_{ni} don't depend very much on the starting point β_0; the γ_{ni} are more or less constant as a function of β_0 up to a given β_0 for which the value of γ_{ni} drops down to zero.

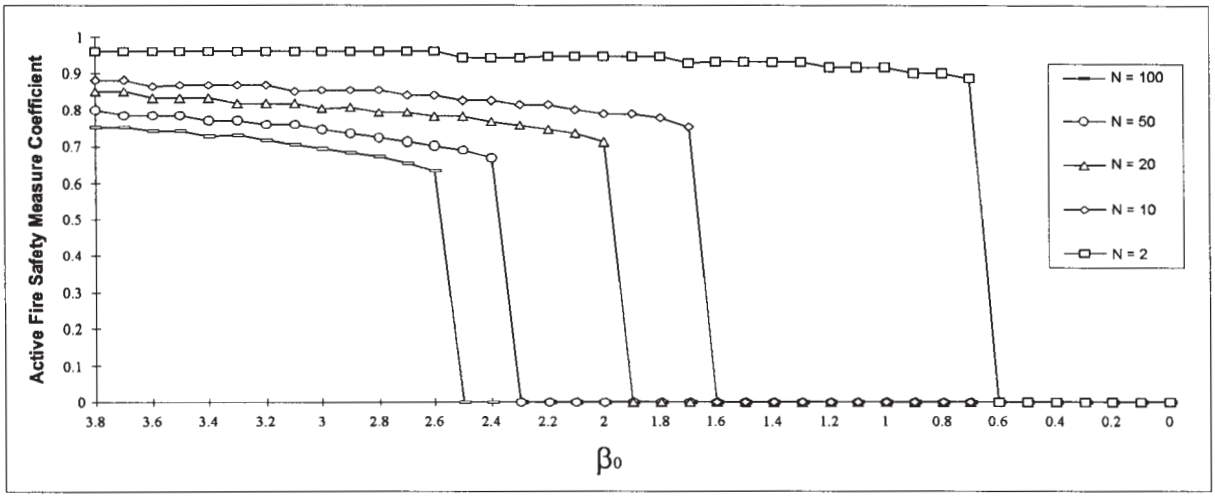


Figure 3.6 : Active Fire Safety Measure Coefficient

The figure enables to deduce the Table 3.3 which shows for each active measure the corresponding reduction of fire probability N and the corresponding factor γ_n.

	Active Measures (A.M)	N	γ_n	γ_{ni}
Automatic Suppression	Sprinkler (S)	100	0,7	0,7
	S + 1 independent Water Supply	100*2	$\gamma_{sprinkler}$*0,95	0,95
	S + 2 independent Water Supply	100*4	$\gamma_{sprinkler}$*0,9	0,9
Manual Fire Suppression	Work Fire Brigade (WFB)	100	0,7	0,7
	Standard Fire Brigade (SFB)	10	0,85	0,85
	SFB + Automatic fire detection by heat	10*4	γ_{SFB}*0,9	0,9
	SFB + Automatic fire detection by smoke (ADS)	10*16	γ_{SFB}*0,8	0,8
	SFB + ADS + Automatic Alarm Transmission to fire Brigade	160*4	$\gamma_{SFB+ADS}$*0,9	0,9
	Fire Fighting Devices (Extinguishers, Hydrants)	10^{-2}	1 / 0,7	1,4

Table 3.3

When some **elementary** fire fighting active measures, as for example a sufficient number of hand extinguishers at each storey are not present, the probability of a fire spread is higher than as usual, which implies a coefficient γ_n greater than 1 (see last line of Table 3.3).

3.3.5 SENSITIVITY ANALYSE OF THE DIFFERENT PARAMETERS (β, α, V, STATISTICAL LAW)

The product of the three factors γ_{q1}, γ_{q2} and γ_n leads to the global factor γ which multiplies the characteristic fire load to give a design fire load considering implicitly the risk of fire and the influence of the active fire fighting measures.

Herebeneath the different parameters (β, α, characteristic value, statistical law, variation coefficients V_s) influencing the coefficients γ_{q1}, γ_{q2} and γ_n are analysed.

- In the previous tables (Tables 3.2 and 3.3) a value of 3,0 for β has been chosen to read in Figure 3.6 the values for γ_{q2} and γ_{ni} . This could be justified by the fact that β = 3,8 is the safety factor adopted in the Eurocode 1 part 1 [24] corresponding to a p_t of $7{,}25.10^{-5}$. By using the following equation :

$$\beta_{fi} = \phi^{-1}\left(\frac{p_t}{p_{acc}}\right)$$

with $p_t = 7{,}25.10^{-5}$, p_{acc}, the fire probability and ϕ is the standard normal distribution function

it appears that $\beta_{fi} = 3{,}0$ corresponds to a fire probability of 0,05 per building and per building life, which is a very high value (1 building on 20 would be subjected to a fire!). Moreover, the curves of γ_{ni} (Figure 3.6) are such that the smaller the value of β is, the lower the coefficient γ_n ; this means that a γ_n corresponding to β_0 is conservative compared to the γ_n which would be deduced from other β smaller than β_0. This conclusion is also well highlighted by the Figure 3.7.

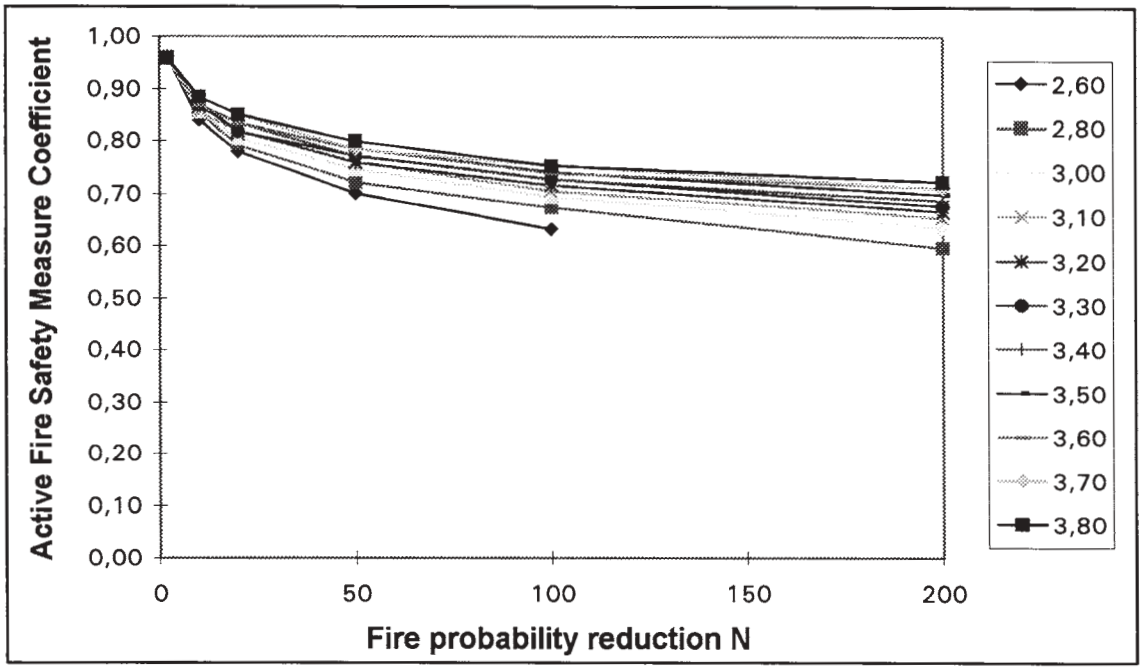


Figure 3.7

The γ_n of Table 3.3 are thus very strongly on the safe side.

- The fire loads has been considered as the main action so that the weighing factor α_{qf} is equal to -0,7 according to Annex A of ENV 1991-1 [24]. This assumption has been checked in Annex A of this paper. A higher value of $(-\alpha_{qf})$ (0,8 ; 0,9 ; 1,0) would lead to smaller γ_{q2} and γ_n .

- The Figures 3.6 and 3.7 are identical whatever the fractile 50%, 80%, 90% or 95% which has been chosen for the **characteristic value**. This implies that the values for γ_{q2} and γ_{ni} don't depend on the chosen characteristic value of the fire load. On the other hand, γ_{q1} depends on the characteristic value and on the reference case.

- Another statistical law (Lognormal instead of Gumbel) doesn't change very much the values of γ (see Annex B of this chapter).

- The Figure 3.8 shows that the higher the **variation coefficient V_S** are, smaller the γ values. This means that the results obtained for a variation coefficient $V_S = 0,25$ are on the safe side for other higher V_S ($V_S \geq 0,25$). According to the following table [5], the results could be extended for all the building types.

Type of building	V_S	V_R
- industrial buildings	0,25	
- business building	0,30	
- schools, hospitals, hotels	0,35	0,25
- dwellings	0,40	

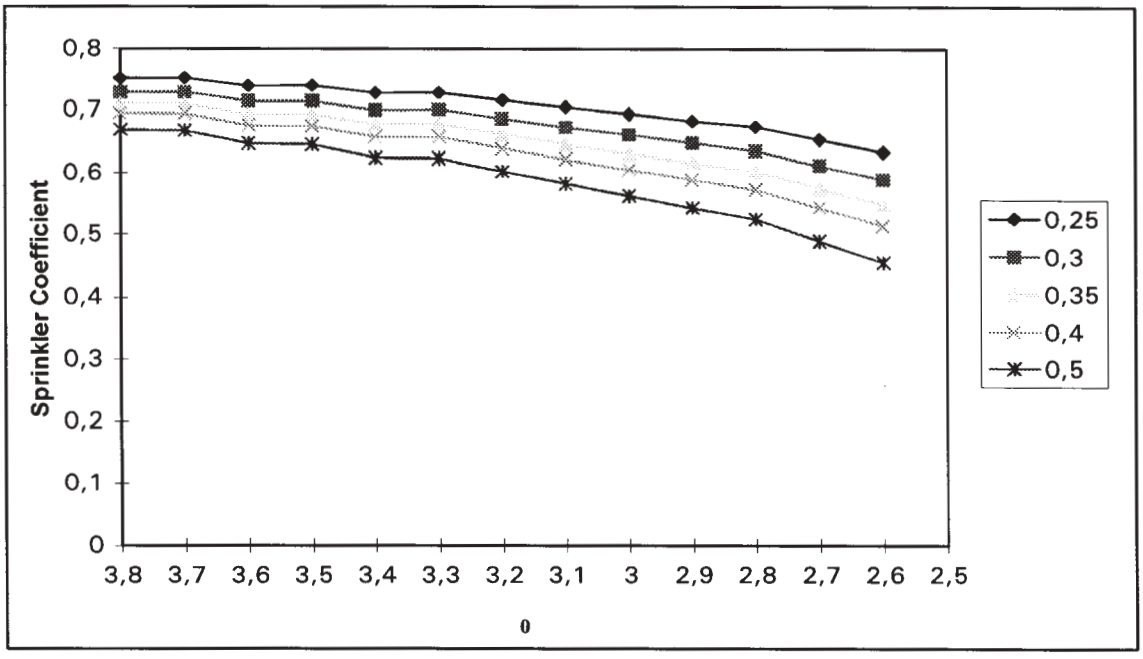


Figure 3.8 : Sprinkler factor for different variation coefficient of the fire load V_S.

Is it allowed to replace the γ_n by the product of the γ_{ni} corresponding to the i active measures ?

For instance, a fire probability reduction N can be obtained by different combinations of active measures :

- either only one measure implying a fire probability reduction N leading to a corresponding γ_n ;
- or two different measures with a fire probability reductions N_1 and N_2 ($N_1 \cdot N_2 = N$) leading to γ_{n1} and γ_{n2}.

Is it on the safe side to use $\gamma_{n1} \cdot \gamma_{n2}$ instead of γ_n ?

On the Figure 3.9, the dotted line represents the factor γ_n corresponding to $\beta = 3,0$ (see Figure 3.7).

This line has to be compared to the other points obtained by multiplying the subfactors γ_{ni}. The legend (N=20 and N=10) means that the γ_n corresponding to a fire probability reduction of N=200 has been obtained by multiplying $\gamma_{N=20}$ (=0,80) and $\gamma_{N=10}$ (=0,85). The legends N=2 means that the points (see Table 3.4) have been obtained by multiplying successively by 0,95 which is the factor γ_{ni} corresponding to a fire probability reduction N=2. The same procedure has been applied for N=4 and 10.

N = 2	γ = 0,95	N = 4	γ = 0,95	N = 10	γ = 0,85	N = 20 and N = 10	γ = 0,85 and 0,8
2	0,95	4	0,90	10	0,85	20	0,80
4	0,90	16	0,81	100	0,72	200	0,68
8	0,86	64	0,73				
16	0,81	256	0,66				
32	0,77						
64	0,74						
128	0,70						
256	0,66						

Table 3.4

It can be seen that the γ'_N obtained by multiplication of subfactors ($\gamma'_N = \gamma_{N1} \cdot \gamma_{N2} \cdot \gamma_{N3}$ with $N = N_1 \cdot N_2 \cdot N_3$) are always higher that the γ corresponding to N.

The Figure 3.9 attests thus that **the fact to split the general factor γ into different subfactors γ_{q1}, γ_{q2} and γ_{ni} is valid.**

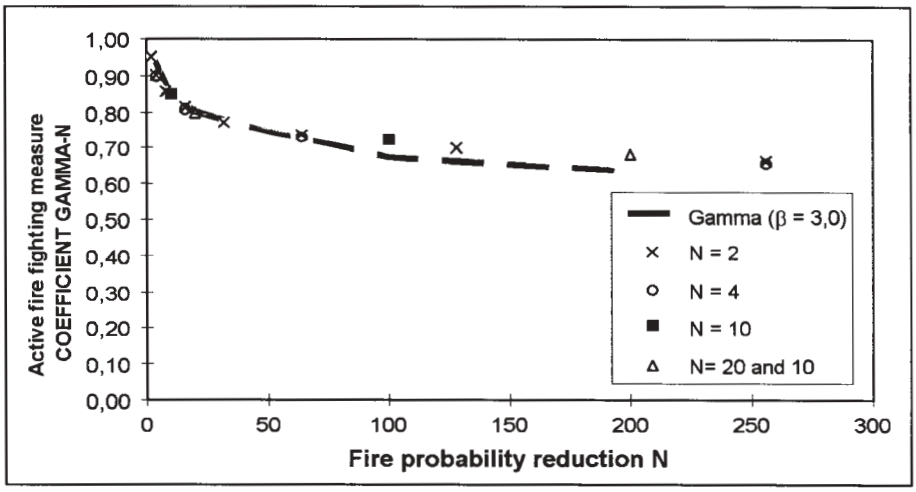


Figure 3.9 : Coefficient γ_n as a function of the fire probability reduction N compared to the results obtained by multiplying subfactors γ_{ni}

3.4 CONCLUSION

In short, the method to calculate the design fire load $q_{f,d}$ can be shared into two levels

- **General Method (Level Two) : Calculation of $\gamma_{q,f}$**

For a compartment, it is possible to calculate the probability of a general fire (Fully Engulfed fire Compartment) depending on the fire compartment size, the type of occupancy and the active fire fighting measures.

Then the safety index β_{fi} depending on the target failure value p_t divided by the probability of a general fire, p_{acc} can be deduced.

$$\beta_{fi} = \phi^{-1}\left(\frac{p_t}{p_{acc}}\right) = \phi^{-1}\left(\frac{7{,}25 \cdot 10^{-5}}{p_{acc}}\right)$$

with $p_{acc} = p_1 \cdot p_2 \cdot p_{n1} \cdots p_{ni}$,

p_{ni} being the failure probability of the active measure i

The Figure 3.2 enables then to deduce the general factor γ_{qf} for the fire load.

- **Simplified Method (Level One) : Calculation of $\gamma_{q,f}$**

For a compartment, the Tables 3.1, 3.2 and 3.3 enable to find the γ_{q1}, γ_{q2} and γ_{ni} . The factor γ_{qf} is equal to $\gamma_{q1} \cdot \gamma_{q2} \cdot \gamma_{n1} \ldots \gamma_{ni}$.

- **Design fire load $q_{f,d}$**

When the factor γ_{qf} has been calculated, the design fire load $q_{f,d}$ can be deduced :

$$q_{f,d} = q_{f,k} \cdot \gamma_{qf}$$

and the temperature field in the compartment can start. The natural fire curve obtained by these methods using the design fire load is a realistic and probabilistic fire curve which defines the thermal action in order to design the structure with a sufficient safety.

4. STUDY OF THE NEW METHODOLOGY BY USING RELIABILITY CALCULATIONS (FORM METHOD) WITH THE SOTFWARE VAP [18]

Introduction

The previous chapter has been based on the Annex A of ENV 1991-1 [24] which assumes a weighing factor α of (-0,7) for the main action and (-0,28) for the secondary action. The fire load density has been considered as the main action. In order to check these assumptions and also to analyse the problem more in details, it was decided to use the reliability method FORM which considers the statistical distribution of each variable, calculates the weighing factor α_i for each variable and deduces the safety index and the corresponding failure probability. The method FORM (First Order Reliability Method) is referred in ENV 1991-1 [24].

The program VAP [18] which enables to deal with the FORM method in an interactive, easy and quick way has been used by the partners to analyse 4 structure types: unprotected steel beam [chapter 4.1 by PA-RE], unprotected steel column [chapter 4.2 by ETH], protected steel beam [chapter 4.3 by CTICM] and protected steel column [chapter 4.4 by ETH].

4.1 UNPROTECTED STEEL BEAM

4.1.1 INTRODUCTION

Reliability methods applied commonly for the persistent design situation may be also used to analyse the accidental (fire) design situation. An example of the steel beam supporting a floor of an office area is used throughout this chapter 4.1. Using partial factor methods as specified in Eurocodes 1 and 3 [1, 24, 35] and ISO 834 [59], the steel beam is firstly designed for both the persistent and accidental (fire) design situation. Then its reliability in the strength domain is analysed using the First Order Reliability Method (FORM [18]).

4.1.2 DETERMINISTIC DESIGN

A simple supported steel beam of a span L exposed to the permanent load G and imposed load Q is considered in the reliability analysis below. In accordance with the Structural Eurocodes [1], [24] and [35] reliability of the beam at the persistent and accidental (fire) design situation should be verified using appropriate load combination and partial safety factors. The following condition should be valid at the persistent design situation

$$(\gamma_G G_k + \gamma_Q Q_k) L^2/8 < W f_{yk}/\gamma_m \qquad (4.1)$$

where notations and numerical values recommended by Eurocodes are applied in this chapter: γ_G = 1,35 denotes the partial safety factor of permanent load G, G_k characteristic value of G, γ_Q = 1,5 partial safety factor of variable load Q, Q_k characteristic value of Q, L is span of the beam, W_{pl} is section modulus, f_{yk} the characteristic value of yield strength f_y, γ_m = 1,1 the partial factor of material property.

As an example (used throughout this chapter) consider the steel beam supporting a floor of an office area having the following input data

$$L = 6 \text{ m}, G_k = 12 \text{ kN/m}, Q_k = 9 \text{ kN/m}, f_{yk} = 235 \text{ MPa} \quad (4.2)$$

which correspond to the loading width 3 m for an office area having the characteristic imposed load 3 kN/m^2. Using data (4.2), it follows from equation (4.1) that the section modulus 625,6 cm^3 is required considering the persistent design situation (not accidental - fire design situation). As an example profile IPE A 330 having W = 701,9 cm^3 may be considered in the design.

In the following reliability consideration the actual profiles are not taken into account and theoretical values of section modulus are considered. However, due to serviceability requirements (deflection, vibration), due to limited choice of "standardised profiles" and, in order to avoid too many different cross sections in the same building, practical design would always lead to a greater sectional modulus than the minimum value. It is reasonable to assume that the actual modulus will be about double of the minimum value determined considering persistent design situation and ultimate limit state only. That's why the section modulus 2 * 625,6 = 1251,2 cm^3 is considered in the following analysis of the example of simply supported beam (note that it would require the profile IPE 400 having W_{pl} = 1307 cm^3).

At the accidental (fire) design situation the following condition is to be considered

$$(G_k + \psi_{1,1} Q_k) L^2/8 < W_{pl} f_{yk} k_y / \gamma_{M,fi} \quad (4.3)$$

where no partial factors γ are used (all partial factors equal unity) while the combination factor $\psi_{1,1}$ = 0,5 may be applied in accordance with equation (9.11) in [24]. The reduction factor k_y of the yield point is introduced in accordance with [35]. It follows from (4.2) and (4.3) that the reduction factor k_y used at the fire design situation should satisfy the condition

$$(G_k + \psi_{1,1} Q_k) * (L^2/8) / (1251{,}2 * f_{yk} / \gamma_{M,fi}) < k_y \quad (4.4)$$

Using data (4.2) and $\gamma_{M,fi}$ = 1 the minimum reduction factor following from equation (4.4) is k_y = 0,2525. However, it follows from (4.18) in ENV 1993-1-2 [35] that the reduction factor k_y of the yield point is a function of the temperature θ

$$k_y = (0{,}9674\ ((1+\exp((\theta - 482)/39{,}19))))^{(-1/3{,}833)} \qquad (4.5)$$

where θ denotes the temperature in the steel. Using data (4.2) and equations (4.4) and (4.5) it follows that the critical temperature θ_{cr} is 690 °C

Taking into account the equation (B.1) in ENV 1991-2-2 [1] improved such that

$\theta_{air} = 20$ for t=0,

$$\theta_{air} = 20 + 1325*(1-0{,}324*\exp(-0{,}2*t/60)-0{,}204*\exp(-1{,}7*t/60)-0{,}472*\exp(-19*t/60)) \qquad (4.6)$$

where t is given in minutes, it follows that t is about 9,40 minutes (0,1565 hour) for $\theta_{air} = 690°C$.

In the following equivalent fire load intensity is recalculated assuming the EC fire curve given by equation (4.6) taking into account data (4.2) supplemented by other required parameters describing a given fire compartment. Further, it is assumed that the maximum steel temperature θ is equal to the maximum air temperature θ_{air} inside the fire-affected compartment, which is on the safe side. Then the corresponding fire load intensity may be calculated from the equation given in Annex B of ENV 1991-2-2 [1] for time t (in hours)

$$t = 0{,}00013\ q_{t,d}\ \Gamma / O \qquad (4.7)$$

where the factor $\Gamma = (O/b)^2/(0{,}04/1160)^2$ defined in Annex B of ENV 1991-2-2 [1] is equal to 1 as the following parameters are considered for the sake of simplicity: the opening factor O = 0,04 $m^{1/2}$ and the factor of the thermal properties of walls is b = 1160 J/ (m^2 $s^{1/2}$ K). Considering the given input data (4.2), equation (4.7) leads to the design value of fire load intensity related to the total surface area A_t as

$$q_{t,d} = 0{,}1565 \times 0{,}04 / 0{,}00013 = 48{,}16\ [MJ/m^2] \qquad (4.8)$$

The design value $q_{f,d}$ of fire load intensity related to the floor surface area A_f is calculated using expression taken from Annex B of [1]

$$q_{f,d} = q_{t,d}\ A_t/A_f = 48{,}16 \times 4 = 192{,}7\ [MJ/m^2] \qquad (4.9)$$

where A_t/A_f = 4 is the assumed ratio of the total and floor surface area of the fire compartment.

Equation (4.9) gives the maximum design value $q_{f,d}$ of fire load intensity which is acceptable in the given office area for the beam designed considering the persistent design situation with a load level of approximately 0,5 (having the section modulus 1251,2 cm^3, which is the double of the minimum value required 625,6 cm^3).

4.1.3 RELIABILITY ANALYSIS

The limit state function in the persistent as well as accidental (fire) design situation may be written as

$$Z = \xi_R R - \xi_E E \tag{4.10}$$

where Z denotes the safety margin, ξ_R the coefficient of model uncertainty for the resistance R and ξ_E the coefficient of model uncertainty for the load effect E.

The resistance R at the persistent design situation is given as

$$R = W f_y \tag{4.11}$$

at the fire design situation as

$$R = W f_y k_y \tag{4.12}$$

where the reduction factor k_y is given by equations (4.5), (4.6) and (4.7).

Finally, the load effect E is given in both design situations as the bending moment at the mid-span point of the beam

$$E = (1/8)\,(G + Q)\,L^2 \tag{4.13}$$

In reliability analysis all basic variables are considered as random variables defined in Table A. The fire load intensity q_f is described by the Gumbel distribution having the coefficient of variation 0,3 and the 80% fractile equal to the design value $q_{f,d}$ =192,7 [MJ/m^2]. The corresponding mean μ_q of q_f is given as μ_q = 192,7/1,216 = 158,5 [MJ/m^2].

Basic variable X	Distribution	Characteristic value X_k	Design value in case of fire	Mean μ_X	Stand.dev. σ_X
$R = W f_y$- resistance[kNm]	Lognormal	294=1251,2 ×235×10^{-3} (5%)	294	350,3=1251,2 ×280×10^{-3}	0,1 × μ_X [1)]
q_f - fire load [MJ/m^3]	Gumbel	192,7 (80%)	192,7	158,5	0,3 × μ_X
$b=(\rho c\lambda)^{0,5}$ [J/m^2 s$^{1/2}$ K]	Constant	1160	1160	1160	0
$O = A_v \sqrt{h}/A_t$ [m$^{1/2}$]	Constant	0,04 m$^{1/2}$	0,04	0,040	0 [2)]
$A_{tf} = A_t / A_f$	Constant	4	4	4	0
G- perman. load [kN/m]	Normal	12 (50%)	12	12	0,1 × μ_X
Q-imposed load [kN/m]	Gumbel	9 (95%)	4,5	5,8	0,3 × μ_X
ξ_R-uncert. of R at 20°C	Normal	1 (50%)	1	1,0	0,1
ξ_R - uncert. of R in fire	Normal	1 (50%)	1	1,0	0,15
ξ_E - uncertainty of E	Normal	1 (50%)	1	1,0	0,1

Table A. Review of basic variables.

Note on Table A:

[1] Recent research of available data concerning yield strength and geometrical data has indicated that the standard deviation could be less than $0,1 \times \mu_X$; this value is considered here as a safe assumption. 0,052 has also been considered in other parts of this document.

[2] Opening factor is usually well known except the case when window glass brakes during the fire; then O may vary considerably (this is, however, not considered here).

Assuming the probabilistic models indicated in Table A, the reliability of the simply supported beam has been analysed using the first order reliability method FORM and the program VAP [18]. It appears that at the persistent design situation the reliability index $\beta = 6,3$ ($\beta = 3,63$ for the original $W = 625,6$ cm^3 and $\beta = 4,5$ if in addition, ξ_R and ξ_E are assumed deterministic and equal to 1,0) is sufficiently high. At the fire design situation $\beta = 0,96$ (the conditional probability of failure $p_{f,fi}$ given the fire flashover is about 0,17). It is interesting to note that approximately the same reliability index $\beta = 0,96$ is obtained when the beam is designed for a given fire load intensity q_f (generally different from that determined by the above recalculation) using equations (4.3), (4.5), (4.6) and (4.7).

Table B shows the sensitivity factors α for all basic variables used in the example of a beam under fire design situation. Obviously, the fire load intensity q_f is the most sensitive basic variable, for which $\alpha_q = - 0,81$. If ξ_R and ξ_E are assumed deterministic and equal to 1,0, α_q becomes 0,902 as shown in Table B. Thus, q_f is the dominating variable affecting the safety; this domination is even higher than the recommendation of in Eurocode 1 [24] to assume the weighting factor $\alpha_q \approx - 0,7$. It appears that reliability of the analysed beam may be well controlled by appropriate design value q_d of the fire load intensity q_f.

X	Characteristic	m	σ	V	Law	α	α ($\xi_R = \xi_E$ = deterministic = 1)
G	12	12	1,2	0,1	N	0,163	0,186
Q	9	5,8	1,73	0,3	G	0,229	0,268
R	294	350,3	35	0,1	LN	-0,244	-0,282
q_f	85	158,5	47,5	0,3	GL	0,808	0,902
ξ_R	1	1	0,15	0,15	N	-0,389	-
ξ_E	1	1	0,1	0,1	N	0,239	-

Table B. Sensitivity factors α for basic variables of a beam under fire design situation.

It is interesting to note that approximately the same values sensitivity factors α, as those indicated in Table B are obtained when the beam is designed for another fire load intensity $q_{f,d}$ using equations (4.3), (4.5), (4.6) and (4.7).

4.1.4 PARTIAL SAFETY FACTOR FOR FIRE LOAD INTENSITY

Design value $q_{d,f}$ of the fire load intensity q_f may be defined similarly as in the case of any action on the bases of the characteristic value q_k and partial factor γ_q using equation

$$q_{f,d} = \gamma_q \, q_{f,k} \tag{4.14}$$

If the fire load intensity q_f is described by Gumbel distribution and the characteristic value q_k is 80% fractile then in accordance with Eurocode recommendation given in Eurocode 1 [24] the partial factor γ_q can be determined as

$$\gamma_q = \frac{q_{f,d}}{q_{f,k}} = \frac{\left(1 - v_q (0{,}45 + 0{,}78 \ln(-\ln(\Phi(\alpha\beta))))\right) \times 1{,}05}{1 - v_q (0{,}45 + 0{,}78 \ln(-\ln(0{,}8)))} \tag{4.15}$$

In this relationship Gumbel distribution having the coefficient of variation v_q is assumed for the fire load intensity q_f. The weighting factor α = 0,7; 0,9 and 1,0, the coefficient of variation v_q = 0,3 (see Table B) are considered in this study.

The partial factor γ_q should be generally derived from the target probability $p_{t,fi}$ of a failure under fire design situation, which may be further derived from the overall target failure probability of failure p_t using the following simplified condition [29]

$$p_{fi} \times p_{t,fi} \leq p_t \tag{4.16}$$

Here p_{fi} denotes the probability of severe fire, which should be determined according to the values of the WG4 report.

Figure A shows a diagram of factor γ_q versus reliability index β obtained by reliability analysis and by approximation (4.15) recommended by Eurocode 1 [24]. Reliability analysis of the beam under fire design has been using programs VAP [18] and input data Table A. The results shown in Figure A were derived assuming both a constant section modulus W (and considering variable characteristic value q_k [Procedure 1]) and a constant characteristic value q_k (and designing section modulus W using equation (4.3), (4.5) (4.6) and (4.7) [Procedure 2]). Thus, the results showed in Figure A are approximately valid for any characteristic value q_k as long as it is defined as 80% fractile of q_f.

Both procedures lead to similar results as shown by Figure B and Tables C and D.

The Figure A shows that the γ_{qf} curve corresponding to α = -0,9 is a safe approximation of the curve obtained by VAP calculations.

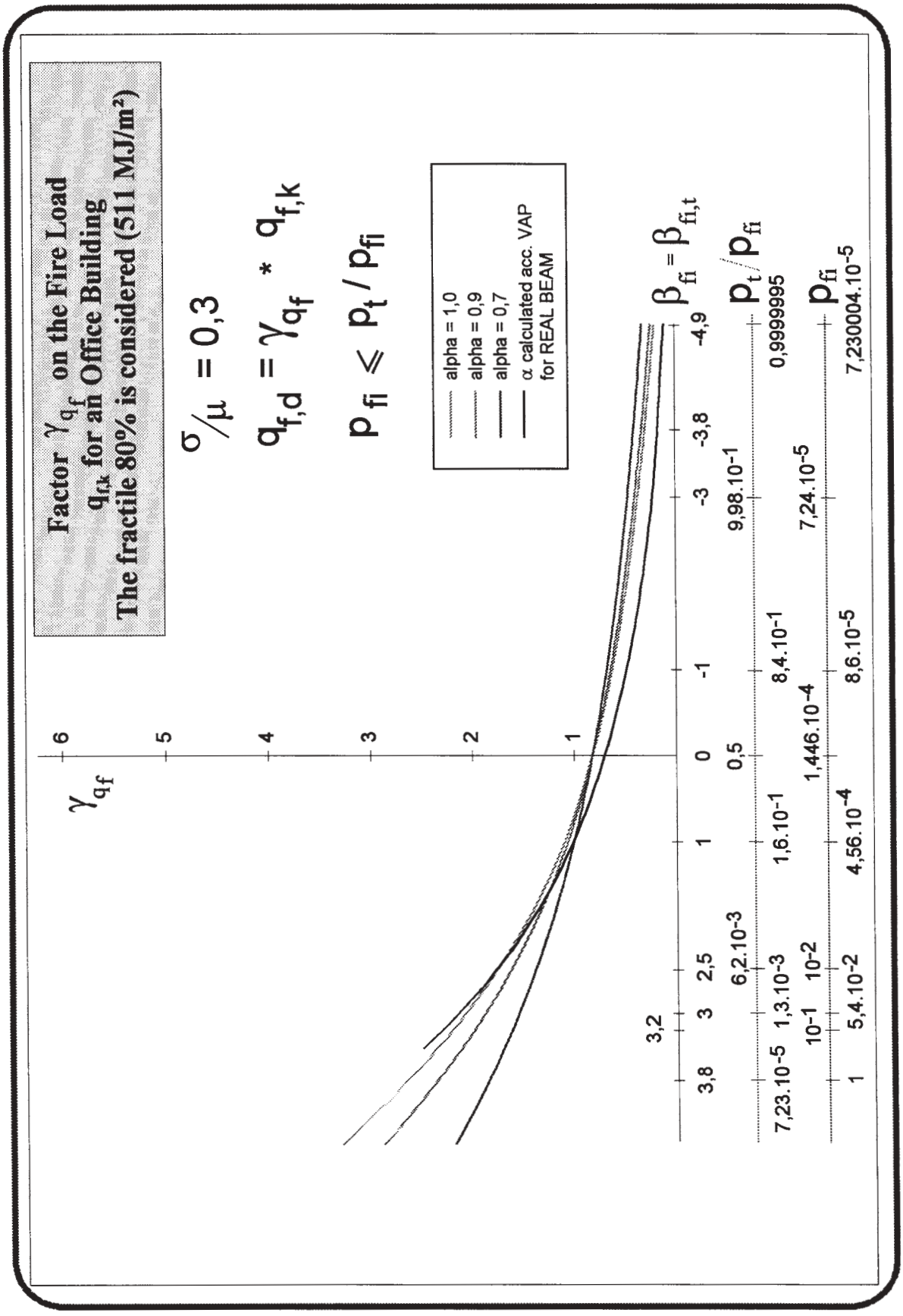


Figure A

f:\fig_a.ds4

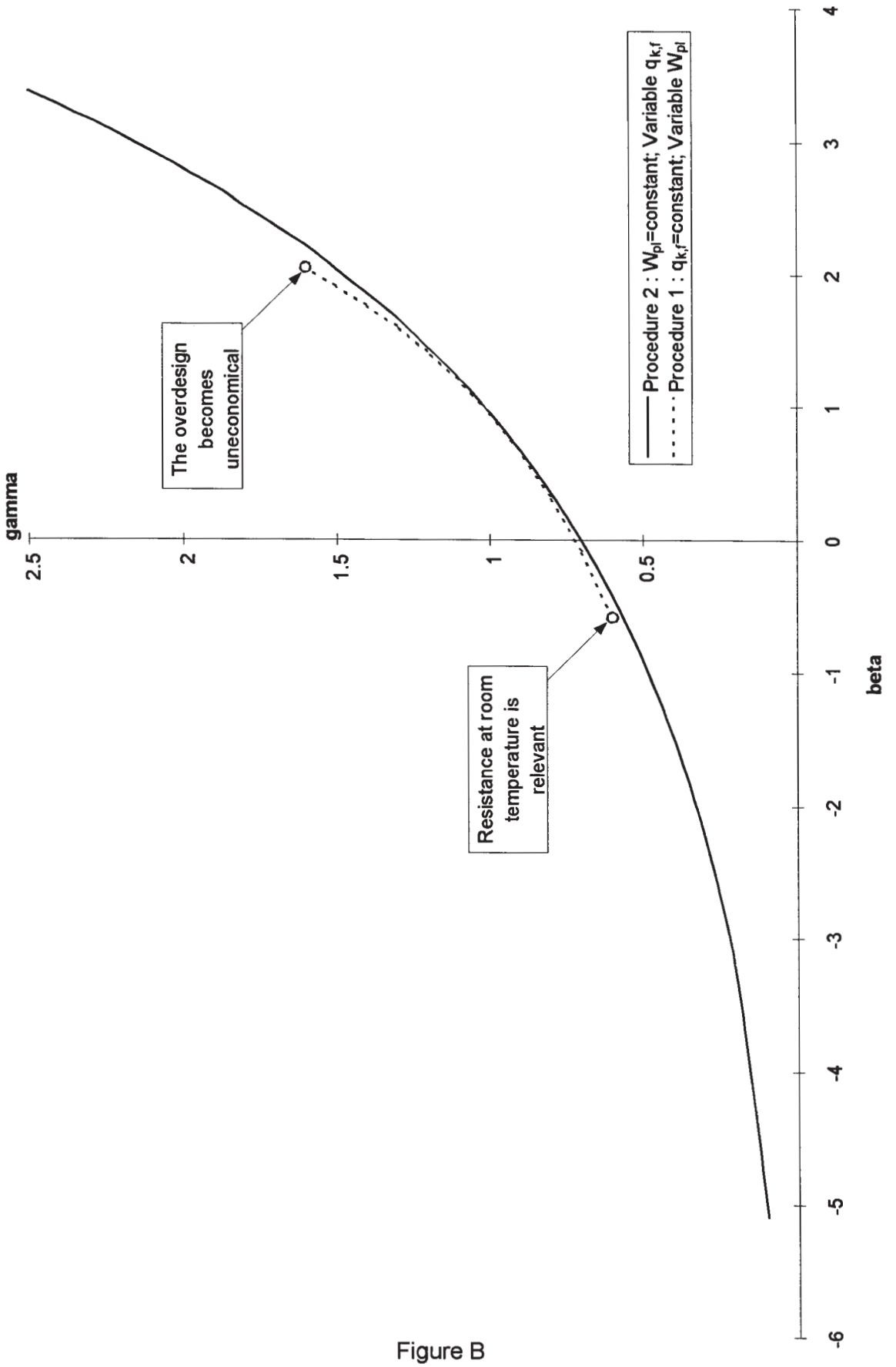

gamma
2.5
2
1.5
1
0.5
0
-1
-2
-3
-4
-5
-6
beta
1
2
3
4
The overdesign becomes uneconomical
Resistance at room temperature is relevant
Procedure 2 : W_{pl}=constant; Variable $q_{k,f}$
Procedure 1 : $q_{k,f}$=constant; Variable W_{pl}

Figure B

Fire load for VAP calculation: procedure 1

qk,f = **192.7** [MJ/m²] m = **158.5**

Gk = 12 kN/m s = 47.55 Rk cold = 147.016 Constant $q_{k,f}$

Qk = 9 kN/m Variable W_{pl}

psi1,1 = 0.5

L = 6 m

fyk = 23.5 kN/cm² 28

gamma	qf,d [MJ/m²]	qt,d [MJ/m²]	t [h]	teta [°C]	ky	W [cm3]	Rk [kNm]	Rm [kNm]	beta	pf,fi
0.1	19.27	4.8175	0.01565688	189.365352	1.00853393	313.283903	147.016	175.168		
0.2	38.54	9.635	0.03131375	317.132302	1.00480155	314.447611	147.016	175.168		
0.3	57.81	14.4525	0.04697063	413.96051	0.96686851	326.784298	147.016	175.168		
0.4	77.08	19.27	0.0626275	487.767902	0.8252289	382.872495	147.016	175.168		
0.5	96.35	24.0875	0.07828438	544.436122	0.63427276	498.14128	147.016	175.168	-0.654	0.743
0.6	115.62	28.905	0.09394125	588.334467	0.48871008	646.513051	151.930567	181.023654	-0.581	0.719
0.7	134.89	33.7225	0.10959813	622.709006	0.39251971	804.946703	189.162475	225.385077	-0.0867	0.535
0.8	154.16	38.54	0.125255	649.971574	0.32853103	961.727863	226.006048	269.283802	0.324	0.373
0.9	173.43	43.3575	0.14091188	671.914399	0.28431363	1111.29898	261.155261	311.163716	0.667	0.252
1	192.7	48.175	0.15656875	689.869518	0.2524713	1251.45886	294.092831	350.40848	0.955	0.17
1.1	211.97	52.9925	0.17222563	704.827158	0.22863633	1381.92146	324.751543	386.938008	1.2	0.115
1.2	231.24	57.81	0.1878825	717.523665	0.210157	1503.43526	353.307287	420.961874	1.41	0.0791
1.3	250.51	62.6275	0.20353938	728.506808	0.19536997	1617.22628	380.048176	452.823359	1.6	0.0551
1.4	269.78	67.445	0.21919625	738.184279	0.18319968	1724.66154	405.295462	482.905231	1.76	0.0391
1.5	289.05	72.2625	0.23485313	746.859712	0.17293198	1827.06197	429.359562	511.577351	1.91	0.0281
1.6	308.32	77.08	0.25051	754.759438	0.16408166	1925.61099	452.518584	539.171079	2.05	0.0203
1.7	327.59	81.8975	0.26616688	762.052354	0.15631238	2021.32062	475.010346	565.969774	2.17	0.0149
1.8	346.86	86.715	0.28182375	768.86468	0.14938679	2115.02941	497.031911	592.208235	2.29	0.0109
1.9	366.13	91.5325	0.29748063	775.290921	0.1431345	2207.41648	518.742872	618.076613	2.41	0.00809
2	385.4	96.35	0.3131375	781.402007	0.13743124	2299.02206	540.270184	643.726177	2.51	0.006
2.1	404.67	101.1675	0.32879438	787.251339	0.13218486	2390.26948	561.713328	669.275454	2.62	0.00446
2.2	423.94	105.985	0.34445125	792.879281	0.12732591	2481.48583	583.14917	694.816033	2.71	0.00332
2.3	443.21	110.8025	0.36010813	798.316498	0.1228011	2572.92027	604.636263	720.417676	2.81	0.00248
2.4	462.48	115.62	0.375765	803.58643	0.11856884	2664.75955	626.218494	746.132674	2.9	0.00185
2.5	481.75	120.4375	0.39142188	808.707137	0.11459605	2757.14089	647.928108	771.999448	2.99	0.00138

Table C

procedure 2

qf,d = **192.7** [MJ/m²]
qf,mean = **158.5** [MJ/m²]
Rd = 294 kNm → m = 350.3, s = 35.03

Constant W_{pl}
Variable $q_{k,f}$

gamma	m	s	beta	pf,fi	N = 10	N = 100
0.1	1585	475.5	-5.09	1	0	0
0.2	792.5	237.75	-3.29	1	0	0
0.3	528.333333	158.5	-2.25	0.988	0	0
0.4	396.25	118.875	-1.5	0.934	0	0
0.5	317	95.1	-0.917	0.82	0	0
0.6	264.166667	79.25	-0.429	0.666	0	0
0.7	226.428571	67.9285714	-0.0112	0.504	0	0
0.8	198.125	59.4375	0.35	0.363	0	0
0.9	176.111111	52.8333333	0.67	0.252	0	0
1	158.5	47.55	0.954	0.17	0	0
1.1	144.090909	43.2272727	1.21	0.113	0	0
1.2	132.083333	39.625	1.44	0.0747	0.5	0
1.3	121.923077	36.5769231	1.66	0.0487	0.61538462	0
1.4	113.214286	33.9642857	1.85	0.0321	0.64285714	0
1.5	105.666667	31.7	2.03	0.021	0.66666667	0
1.6	99.0625	29.71875	2.21	0.0137	0.6875	0.125
1.7	93.2352941	27.9705882	2.36	0.0091	0.70588235	0.29411765
1.8	88.0555556	26.4166667	2.51	0.00599	0.72222222	0.38888889
1.9	83.4210526	25.0263158	2.66	0.00396	0.73684211	0.42105263
2	79.25	23.775	2.79	0.00263	0.75	0.45
2.1	75.4761905	22.6428571	2.92	0.00176	0.76190476	0.47619048
2.2	72.0454545	21.6136364	3.04	0.00118	0.77272727	0.5
2.3	68.9130435	20.673913	3.16	0.000791	0.7826087	0.52173913
2.4	66.0416667	19.8125	3.27	0.000535	0.79166667	0.54166667
2.5	63.4	19.02	3.38	0.000363	0.8	0.56

Table D

4.2 UNPROTECTED STEEL COLUMN

4.2.1 INTRODUCTION

4.2.1.1 Reference case

In order to study the influence of active measures on the fire design of steel columns the failure probability of massive unprotected steel column is determined and compared it with a given target probability.

For the reference case we define that the column as standing in an office with an area of 50 m^2. The geometrical dimensions and the assumptions regarding the distribution of the fire load are the same as in the WG3 report.

Room:	Room width	b	= 5,0 m
	Room length	l	= 10,0 m
	Room height	h	= 4,0 m
	Floor area	A	$= 5{,}0 \cdot 10{,}0 = 50\ m^2$
	Total room area	A_t	$= (2 \cdot 50) + (5{,}0 + 10{,}0) \cdot 2 \cdot 4{,}0 = 220\ m^2$
	Ventilation area	A_v	$= b_w \cdot h_w = 4{,}4 \cdot 1{,}6 = 7{,}0\ m^2$
	Opening factor	O_f	$= \frac{7{,}0\ m^2 \sqrt{1{,}6\ m}}{220\ m^2} = 0{,}04$

4.2.1.2 Structural system and loads

For the reference case we consider a steel column with the following properties:

Solid column:	Room height	h	= 4,0 m
	Buckling length:	l_{cold}	= 4,0 m
	Buckling length:	l_{fire}	= 2,0 m
	Self weight:	P	= 2000 kN
	Imposed load:	N	= 2000 kN

4.2.1.3 Calculation procedure

The calculations are made according the following steps:

- definition of the target probability
- determination of the reference section at room temperature
- determination of the reliability of the column at room temperature
- determination of the reference section in case of fire (for example ISO fire resistance R60)
- determination of the reliability of the column in case of fire including the massivity factor

4.2.2 TARGET PROBABILITY

4.2.2.1 Target probability without sprinkler system

For this example the target probability for fifty years lifetime is taken according to Eurocode 1 Annex A Table A.2 [24]: $\mathbf{p_{accepted} = 7{,}25 \,.\, 10^{-5}}$

Note: For fire a greater target probability could be accepted (see [44] and Annex B of this report) but this is not considered in this example.

From the statistical survey of fires in the canton of Berne [39] we find an occurrence frequency of severe fires of $\mathbf{p_{FRI} = 0{,}4 \,.\, 10^{-6} \,/\, m^2 \,.\, year}$ without automatic fire suppression system.

For our office example with A = 50 m^2 and $t_{building-lifetime}$ = 50 years an accepted failure probability of the column given a severe fire is:

$$\mathbf{p_{target} = \frac{p_{accepted}}{p_{FRI} \cdot t_{building-lifetime} \cdot Area} = \frac{7{,}25 \,.\, 10^{-5}}{0{,}4 \,.\, 10^{-6}\ 50\,years \,.\, 50\,m^2} = 0{,}0725}$$

4.2.2.2 Target probability with sprinkler system

The probability that a sprinkler system fails to prevent a severe fire is assumed to be 0,02 [45].

$$\mathbf{p_{target} = \frac{p_{accepted}}{p_{FRI} \cdot p_{sprinkler-failure} \cdot t_{building-lifetime} \cdot Area} = \frac{7{,}25 \,.\, 10^{-5}}{0{,}4 \,.\, 10^{-6} \,.\, 0{,}02 \,.\, 50\,years \,.\, 50\,m^2}}$$

$$\mathbf{= 3{,}625 \geq 1{,}0}$$

For our office example with A = 50 m^2, $t_{building-lifetime}$ = 50 years and a sprinkler system there is no need to have a fire resistance because the accepted failure probability is larger than the probability of a severe fire able to damage the structure.

4.2.3 REFERENCE SECTION FOR ROOM TEMPERATURE

4.2.3.1 Structural system and loads (see chapter 4.2.1.2)

Solid column:	Room height	h	= 4,0 m
	Buckling length:	l_{cold}	= 4,0 m
	Self weight:	P	= 2000 kN
	Imposed load:	N	= 2000 kN

4.2.3.2 Load level for room temperature design

The design load according to EC1 part 1-1 at room temperature is:

$S_d = 1{,}35 \cdot P + 1{,}5 \cdot N = 1{,}35 \cdot 2000\ kN + 1{,}5 \cdot 2000\ kN = 5700\ kN$ [24] Table 9.2

4.2.3.3 Design for room temperature

∅ = 230 mm

A= 41547,6 mm^2
A_m/V= 17,4
I= 137,367*10^6 mm^4
i= 57,5 mm
l = 4,0 m

$$R_{d,20°C} = \kappa_{c,20°C} \cdot A \cdot f_y = 6828{,}0 \text{ kN}$$

$$\text{with } \kappa_{c,20°C} = \frac{1}{\varphi + \sqrt{\varphi^2 - \bar{\lambda}_{20°C}^{\,2}}} = 0{,}69928$$

$\alpha_c = 0{,}49$

$$\varphi = 0{,}5 \cdot \left[1 + \alpha_c \cdot \left(\bar{\lambda}_{20°C} - 0{,}2\right) + \bar{\lambda}_{20°C}^{\,2}\right] = 0{,}907$$

$$\bar{\lambda}_{20°C} = \frac{\ell_{k,cold}}{\sqrt{I/A} \cdot \pi \cdot \sqrt{E/f_y}} = \frac{4000}{\sqrt{137{,}367 * 10^6 / 41547{,}56} * \pi * \sqrt{210000/235}} = 0{,}741$$

$S_d \leq R_d / \gamma_R$
5700 kN $\leq$ 6828,0 / 1,1 = 6207,3 kN

$\eta = N_d / R_d$ = 5700 kN / 6828,0 kN = 0,8348 = 0,83

The column fulfils the requirement at room temperature.

(Note: ∅ = 220 mm: R_d / γ_R = 6058,7 /1,1 = 5508 kN $\leq S_d$ = 5700 kN)

4.2.4 RELIABILITY OF THE COLUMN AT ROOM TEMPERATURE

4.2.4.1 The supply-demand R-S reliability-based format

The term reliability is here defined as the probabilistic measure of assurance of performance. The probability of structural failure $p_f = p[G(X) \leq 0]$ using the FORM (First Order Reliability Method) procedures is hereafter calculated using the program VaP [18].

4.2.4.2 Limit state function G for room temperatures

G = R -(N+P)
=((1/((0,5*(1+0,49*((lk/((I/A)^0,5)/(p*((E/fy)^0,5)))-0,2)+(lk/((I/A)^0,5)/(p*((E/fy)^0,5)))^2))+((0,5*(1+0,49*((lk/((I/A)^0,5)/(p*((E/fy)^0,5)))-0,2)+(lk/((I/A)^0,5)/(p*((E/fy)^0,5)))^2))^2-(lk/((I/A)^0,5)/(p*((E/fy)^0,5)))^2)^0,5))*A*fy/1000) - (N+P)

4.2.4.3 Probability density function (PDF) for each variable (cold)

Self weight [24], [29], [30]:

P: law: Gaussian
nominal value : 50% fractile = 2000 kN
$V_Q = 0,1$
$m_Q = 2000$ kN
$\sigma_Q = m_Q * V_Q = 200$ kN

Variable load [24], [29], [30]:

N: law: Gumbel Type I
nominal value : 95% fractile = 2000 kN
$V_N = 0,3$
$m_N = 2000$ kN/1,56 = 1282,0
$\sigma_N = m_N * V_N = 384,61$

Structural steel:

R: law: lognormal
nominal value : 95% fractile = 235 N/mm^2
$V_R = 0,052$ [30] (Table 2.3)
$m_R = e^{1,645 V_R} * 235$ N/mm^2 = 255,987 [30] (2.5)
$\sigma_R = m_R * V_R = 13,3$

	nominal	fractile	m	σ	V	Law
P	2000	50%	2000	200	0,1	N
N	2000	95%	1282,05	384,61	0,3	GL
R	235	95%	255,987	13,3	0,052	LN

Table 4.1: Summary of the variables

4.2.4.4 Input of Variables of G[1] for FORM Analysis with VaP:

A	D	4,155e+04	
I	D	1,374e+08	
E	D	2,100e+05	
N	GL	1109,0	0,003
P	N	2,000e+03	200,000
f_y	LN	5,544	0,052
l_k	D	4,000e+03	

[1] vgl calculation Column K6

4.2.4.5 Results of FORM Analysis of G:

∅ = 230 mm β = HL - Index = 4,62 $p(G<0) = 1{,}9 \cdot 10^{-6}$

For a comparison a crude Monte Carlo Analysis of G was performed with 1.000.000 samples:
mean = 3934 kN sdev = 496,2 kN skew = -0,525 kurt = 3,85 p (G<0) = 0,000002

(Note: ∅ = 220 mm: β = HL - Index = 4,03 $P(G<0) = 2{,}7 \cdot 10^{-5}$)

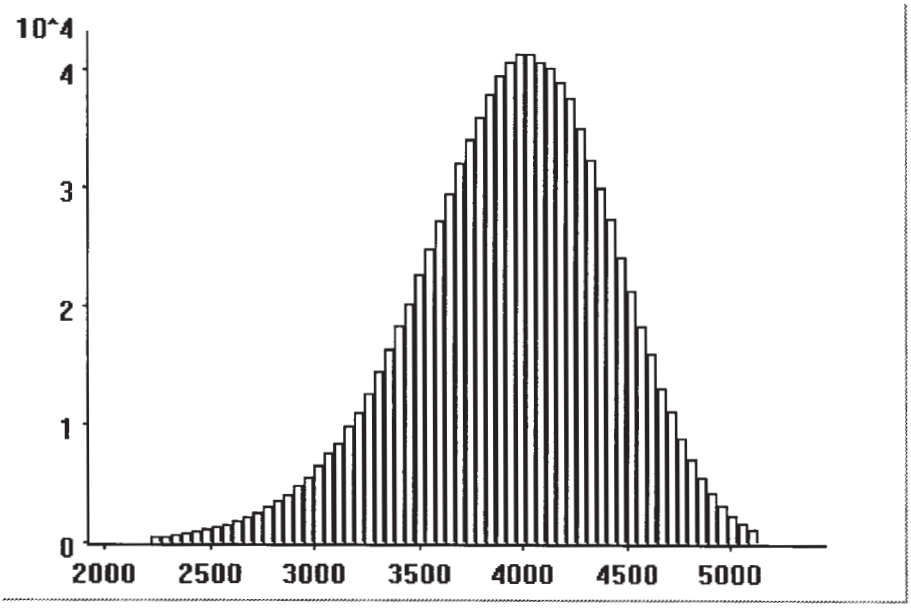


Figure 4.1: Monte Carlo Analysis of G (with the buckling length l = 4 m)

For the column a failure probability of $1{,}9 \cdot 10^{-6}$ was found for 1 Mio. Monte Carlo samples. The column fulfils the target probability $p(G<0) = 1{,}9 \cdot 10^{-6} < 7{,}25 \cdot 10^{-5}$.

4.2.5 REFERENCE SECTION IN CASE OF FIRE RESISTANCE (R60)

4.2.5.1 Structural system and loads

Let us consider a steel column 4 m long with the following loads

Solid column: Buckling length: l_{cold} = 4,0 m
Buckling length: l_{fire} = 2,0 m
Self weight: P = 2000 kN
Imposed load: N = 2000 kN

4.2.5.2 Load level for fire design

The design load at room temperature is calculated to [1]

$N_{fi,d} = 1{,}0 \cdot P + 0{,}5 \cdot N = 1{,}0 \cdot 2000\ kN + 0{,}5 \cdot 2000\ kN = 3000\ kN$ [24] Table 9.3

4.2.5.3 Design for ISO-fire resistance R60

$\varnothing = 250$ mm with $A = 49087{,}4\ mm^2$

$A_m/V = 16{,}0$

$I = 191{,}75 * 10^6\ mm^4$

$i = 62{,}5$ mm

Resistance $R_{d,20°C}$ at room temperature with the buckling length in case of fire $l_{fire} = 2{,}0$ m:

$$R_{d,20°C} = \kappa_{c,20°C} \cdot A \cdot f_y = 10707{,}9\ kN$$

with $$\kappa_{c,20°C} = \frac{1}{\varphi + \sqrt{\varphi^2 - \bar{\lambda}_{20°C}^{\,2}}} = 0{,}92863$$

$a_c = 0{,}49$

$$\varphi = 0{,}5 \cdot \left[1 + \alpha_c \cdot \left(\bar{\lambda}_{20°C} - 0{,}2\right) + \bar{\lambda}_{20°C}^{\,2}\right] = 0{,}5925$$

$$\bar{\lambda}_{20°C} = \frac{\ell_{k,fire}}{\sqrt{I/A} \cdot \pi \cdot \sqrt{E/f_y}} = \frac{2000}{\sqrt{191{,}75 * 10^6 / 49087{,}4} * \pi * \sqrt{210000/235}} = 0{,}3407$$

load level $\eta = N_{fi,d} / R_d = 3000\ kN / 10707{,}9\ kN = 0{,}28$

Note: The results of the research 7210-SA/316/515/618/931 "Buckling Curves in Case of Fire" should be used in the future and leads to a smaller load level.

4.2.5.4 Resistance in case of fire (R60)

The design in case of fire is an iterative calculation. The starting values are the $\eta = 0{,}28$ and $\kappa = 1{,}2$. With these values a critical temperature of $\theta_{cr} = 647°C$ can be calculated [35].

$$R_{d,647°C} = \kappa_{c,647°C} \cdot A \cdot f_y = 10162{,}5\ kN$$

with $\gamma_{M,fire} = 1{,}0$

$\theta_{cr} = 647\ °C$

$k_{y,\theta max} = 0{,}36$

$k_{E,\theta max} = 0{,}2254$

$$\bar{\lambda}_{20°C} = \frac{\ell_{k,fire}}{\sqrt{I/A} \cdot \pi \cdot \sqrt{E/f_y}} = \frac{2000}{\sqrt{191,75 * 10^6 / 49087,4} * \pi * \sqrt{210000/235}} = 0,3407$$

$$\bar{\lambda}_{\theta max} = \bar{\lambda}_{20°C} \cdot \sqrt{k_{y,\theta max} / k_{E,\theta max}} = 0,43$$

$$\alpha_c = 0,49$$

$$\varphi = 0,5 \cdot \left[1 + \alpha_c \cdot \left(\bar{\lambda}_{\theta max} - 0,2 \right) + \bar{\lambda}_{\theta max}^2 \right] = 0,649$$

$$\kappa_{c,\theta max} = \frac{1}{\varphi + \sqrt{\varphi^2 - \bar{\lambda}_{\theta max}^2}} = 0,881$$

$\eta = N_{fi,d} / R_{fi,d,20°C} = 3000$ kN / 10162,5 kN = 0,295 = 0,30

In a second iterative step and the values h = 0,30 and k =1,2 the critical temperature can be evaluated from [35] as q_{cr} = 640°C and the fire resistance time is found from the nomogram [31] as 63 minutes.

4.2.6 RELIABILITY OF THE COLUMN IN CASE OF FIRE INCLUDING THE MASSIVITY FACTOR

4.2.6.1 Structural system and loads

Let us consider a steel column with the same structural system, section and loads as in chapter 5:

Solid column:	Buckling length:	l_{cold}	= 4,0 m
	Buckling length:	l_{fire}	= 2,0 m
	Self weight:	P	= 2000 kN
	Imposed load:	N	= 2000 kN

4.2.6.2 Load level for fire design

The design load for fire design is calculated to [1]

$N_{fi,d} = 1,0 \cdot P + 0,5 \cdot N = 1,0 \cdot 2000$ kN $+ 0,5 \cdot 2000$ kN = 3000 kN [24] Table 9.3

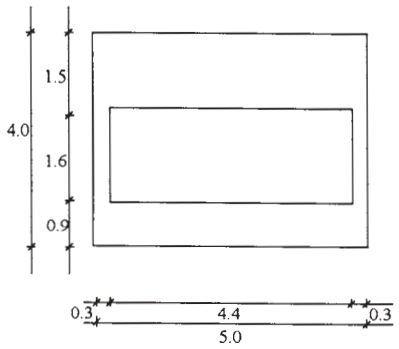
4.2.6.3 Compartment and fire load

The same fire compartment was chosen as in the example for the beam with the following characteristic:

Room:	b	= 5,0 m
	l	= 10,0 m
	h	= 4,0 m
	A	= 5,0 · 10,0 = 50 m^2
	A_t	= (2 · 50) + (5,0 + 10,0) · 2 · 4,0 = 220 m^2

Window:

$b_w = 4{,}4\ m^2$
$h_w = 1{,}6\ m$
$A_v = 7{,}0\ m^2$



$$O_f = \frac{A_v \cdot \sqrt{h_w}}{A_t} = \frac{7{,}0\ m^2 \cdot \sqrt{1{,}6\ m}}{220\ m^2} = 0{,}04$$

with b = 1160

$$\Gamma = \frac{\left(O_f / b\right)^2}{\left(0{,}04 / 1160\right)^2} = \frac{\left(0{,}04 / 1160\right)^2}{\left(0{,}04 / 1160\right)^2} = 1{,}0$$

The distribution of the fire load was chosen for an office assuming a Gumbel distribution, given by the following values (according to the WG3 report):

V:	0,3	[42] and [43]
mean:	430 MJ/m^2	
standard deviation:	130 MJ/m^2	

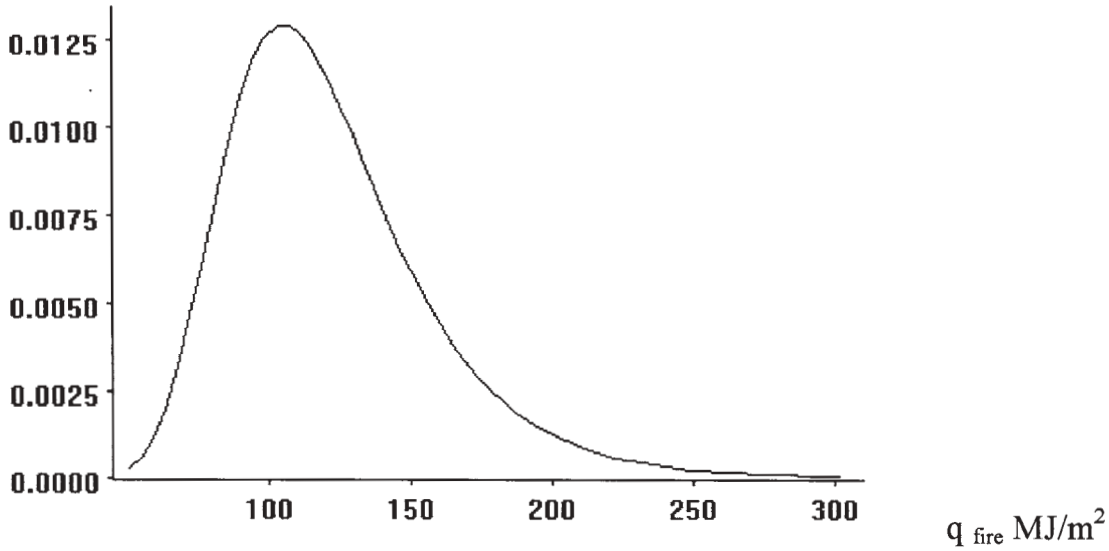


Figure 4.2: PDF of the fire load density in offices

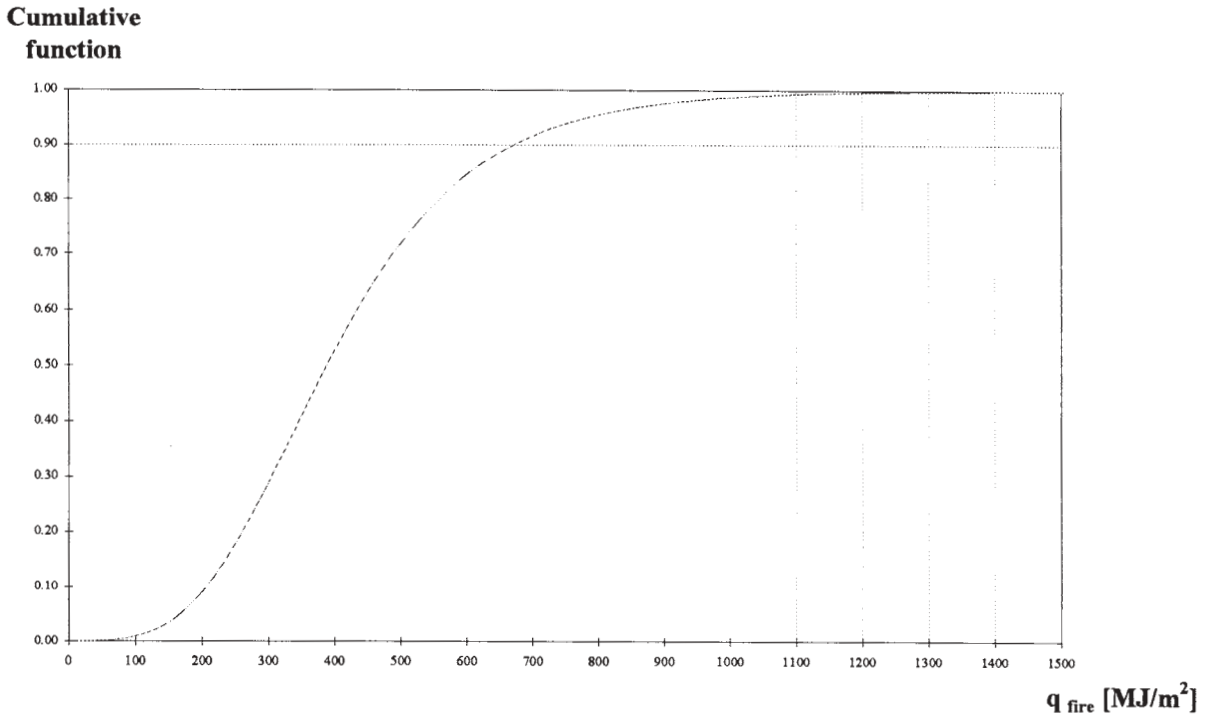


Figure 4.3: Cumulative distribution of the fire load in offices

$$\mu = u + \gamma/\alpha$$
$$\sigma = \frac{\pi}{\alpha \cdot \sqrt{6}} \qquad [44]$$

$$f(x) = \alpha \cdot \exp(\alpha(x-u)-\exp(\alpha(x-u)))$$
$$F(x) = 1- \exp(-\exp(\alpha(x-u)))$$

4.2.6.4 Relation between the fire load and the maximum gas temperature

The maximum gas temperature is calculated according Annex B of ENV 1991-2-2 [1]:

$$\theta_{max,gas} = 1325 \cdot \left(1 - 0{,}324 \cdot e^{-0{,}2 \cdot t_{max}} - 0{,}204 \cdot e^{-1{,}7 \cdot t_{max}} - 0{,}472 \cdot e^{-19 \cdot t_{max}}\right)$$

$$q_{t,d} = q_{f,d} \cdot \left[A_f / A_t \right] \qquad \text{[1] Annex B (B.1)}$$

$$t_{max} = \frac{0{,}00013 \cdot q_{t.d} \cdot \Gamma}{O_f}$$

For $\Gamma = 1{,}0$ the parametric gas temperature follows closely the ISO standard fire curve, Therefore the ISO curve is used in the following calculations to represent the gas temperature (see Figure 4.5) in the office given in chapter 4.2.6.6.

$$\theta_{max,gas} = 20 + 345 \cdot \log_{10}[8 \cdot t_{max} + 1] \quad \text{[1] ISO 834 (4.5)}$$

4.2.6.5 Relation between the gas temperatures and the maximum steel temperature

The heating of the steel is delayed to the gas temperature depending on the massivity factor and can be calculated according to [35] (chapt. 4.2.5).

The calculation of the steel temperature for the gas temperature according to chapter 4.2.6.4 for a fire load of q_{fire} = 560 MJ/m ^{2} (80% fractile) and a column ∅ = 250 mm with $A_m/V = 2 / r = 16$ is given in Figure 4.5 and leads to the following results:

$$\theta_{max} = 441{,}0°C \quad t_{crit} = 64{,}4 \text{ min}$$

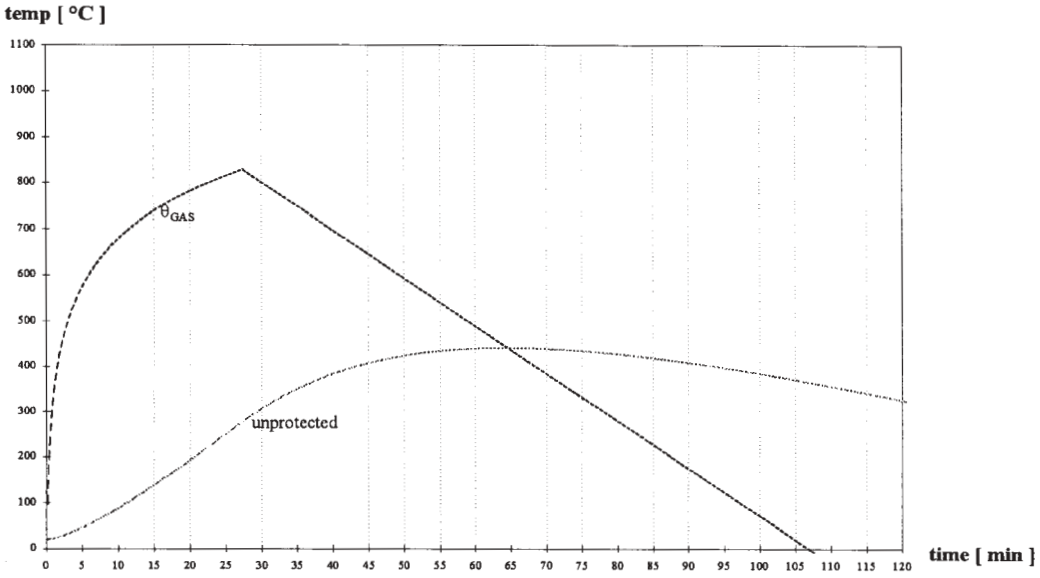


Figure 4.4: Development of the temperature (column ∅ = 250mm, q_{fire}=560 MJ/m ^{2} with Γ = 1,0)

For other column sections the maximum steel temperature is given in Table 4.2.

∅ [mm]	A/V [m^{-1}]	θ_{max} [°C]	t (θ_{max})[min]
470	8,5	301,4	77,8
450	8,9	310,7	76,9
400	10,0	335,0	74,6
350	11,4	363,5	71,8
300	13,3	398,2	68,5
250	16,0	441,0	64,4
200	20,0	492,9	59,4
150	26,7	557,9	53,2
100	40,0	639,9	45,3

Table 4.2: Max. temperature depending on the massivity factor (q_{fire} = 560MJ/m ^{2} with Γ = 1,0)

4.2.6.6 Fitted relation between the fire load and the maximum steel temperature

The increase of the temperature for different massivity factors can be calculated as a function of the fire load (see Figure 4.5) and the results fitted by a polynom to be used in the FORM analysis (see Table 4.3).

∅ = 470mm	A/V = 8,5	$\theta_{max} = 2*10^{-11}q^4 - 8*10^{-8}q^3 + 7*10^{-5}q^2 + 0{,}3958q + 71{,}933$
∅ = 450mm	A/V = 8,9	$\theta_{max} = 1*10^{-11}q^4 - 7*10^{-8}q^3 + 3*10^{-5}q^2 + 0{,}4399q + 68{,}632$
∅ = 400mm	A/V = 10,0	$\theta_{max} = 1*10^{-11}q^4 - 4*10^{-8}q^3 - 5*10^{-5}q^2 + 0{,}5147q + 65{,}771$
∅ = 350mm	A/V = 11,4	$\theta_{max} = -5*10^{-12}q^4 + 6*10^{-8}q^3 - 3*10^{-4}q^2 + 0{,}7036q + 50{,}934$
∅ = 300mm	A/V = 13,3	$\theta_{max} = -2*10^{-11}q^4 + 1*10^{-7}q^3 - 4*10^{-4}q^2 + 0{,}8423q + 48{,}364$
∅ = 250mm	**A/V = 16,0**	$\theta_{max} = -2*10^{-11}q^4 + 2*10^{-7}q^3 - 5*10^{-4}q^2 + 0{,}9244q + 59{,}437$
∅ = 200mm	A/V = 20,0	$\theta_{max} = -3*10^{-11}q^4 + 2*10^{-7}q^3 - 6*10^{-4}q^2 + 0{,}9712q + 89{,}692$
∅ = 150mm	A/V = 26,7	$\theta_{max} = -2*10^{-11}q^4 + 2*10^{-7}q^3 - 5*10^{-4}q^2 + 0{,}9402q + 147{,}13$
∅ = 100mm	A/V = 40,0	$\theta_{max} = -1*10^{-11}q^4 + 1*10^{-7}q^3 - 4*10^{-4}q^2 + 0{,}9279q + 220{,}35$

Table 4.3: Fitted temperature curve for different massivity factors (with Γ = 1)

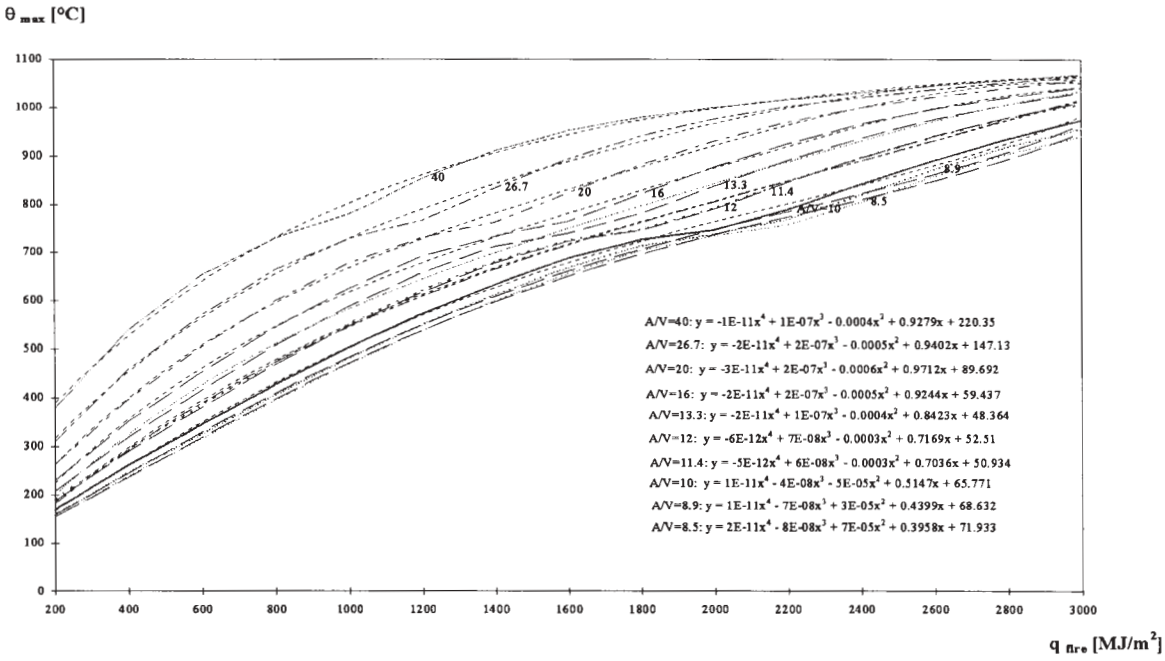


Figure 4.5: Fitted curves of the increase of the temperature depending of the fire load and the massivity factor (with G = 1,0)

4.2.6.7 Design buckling resistance

$$R_{fi,d,\theta max} = \frac{\kappa_{c,\theta max} \cdot A \cdot \left[k_{y,\theta max} / 1{,}2 \right] \cdot f_y}{\gamma_{M,fire}}$$

[35] (chapt. 4.2.3.2)

with $\gamma_{M,fire} = 1{,}0$

$$\kappa_{c,\theta max} = \frac{1}{\varphi + \sqrt{\varphi^2 - \overline{\lambda}_{\theta max}^{\ 2}}}$$

$\alpha_c = 0{,}49$

$$\varphi = \mathbf{0{,}5.}\left[\mathbf{1} + \alpha_c.\left(\bar{\lambda}_{\theta\max} - \mathbf{0{,}2}\right) + \bar{\lambda}_{\theta\max}^{\,2}\right]$$

$$\bar{\lambda}_{\theta\max} = \bar{\lambda}_{fi,0} \cdot \sqrt{k_{y,\theta\max} / k_{E,\theta\max}}$$

As a first assumption we assume

$$\mathbf{t_{max}} = \frac{\mathbf{0{,}00013 \,.\, q_{t.d} \,.\, \Gamma}}{\mathbf{O_f}}$$

$$\bar{\lambda}_{\theta\max} = \mathbf{1{,}2} \,.\, \bar{\lambda}_{20°C}$$

$$q_{t,d} = q_{f,d} \cdot \left[A_f / A_t\right] \qquad \text{[1] Annex B (B.1)}$$

$$\theta_{\max} = 20 + 345 \cdot \log_{10}\left[8 \cdot t_{\max} + 1\right] \qquad \text{[1] ISO 834 (4.5)}$$

$$k_{y,\theta\max} = \left\{ \frac{1}{0{,}9674 \cdot \left\{1 + \exp\left[\frac{20 + 345 \cdot \left(\frac{\ln\left[8 \cdot \left(\frac{0{,}00013 \cdot 60 \cdot qfire,d}{4.O}\right) + 1\right]}{\ln(10)}\right)}{39{,}19}\right]\right\}} \right\}^{\left(1/3{,}833\right)}$$

[35] (chapt. 3.2.1)

$$k_{E,\theta\max} = \frac{1}{\left(e^{\left(\frac{\theta_{max} - 455}{35}\right)} + 3{,}3\right)^{0{,}28}}$$

As a approximation the value for $k_{E,\theta max}$ is introduced hereafter in the FORM equation as given curve (see chapter 6.8)

$$\bar{\lambda}_{fi,0} = \frac{\ell_{k,fire}}{\sqrt{I/A} \cdot \pi \cdot \sqrt{E/f_y}}$$

$$R_{fi,d,\theta max} = \frac{\kappa_{c,\theta max} \cdot A \cdot \left[k_{y,\theta max} / 1,2 \right] \cdot f_y}{\gamma_{M,fire}} = \frac{\left[\left(\frac{1}{\varphi + \sqrt{\varphi^2 - \bar{\lambda}_{\theta max}^{\ 2}}} \right) / 1,2 \right] \cdot A \cdot k_{y,\theta max} \cdot f_y}{1,0}$$

$$= \frac{\left[\left(\frac{1}{0,5 \cdot \left[1 + \alpha_c \left(\bar{\lambda}_{\theta max} - 0,2 \right) + \bar{\lambda}_{\theta max}^{\ 2} \right] + \sqrt{0,5 \cdot \left[1 + \alpha_c \left(\bar{\lambda}_{\theta max} - 0,2 \right) + \bar{\lambda}_{\theta max}^{\ 2} \right]^2 - \bar{\lambda}_{\theta max}^{\ 2}}} \right) / 1,2 \right] \cdot A \cdot k_{y,\theta max} \cdot f_y}{1,0}$$

$$= \frac{\left[\left(\frac{1}{0,5 \cdot \left[1 + \alpha_c \left(\bar{\lambda}_{fi,0} \cdot \sqrt{ky, q\,max / kE, q\,max} - 0,2 \right) + \bar{\lambda}_{\theta max}^{\ 2} \right] + \sqrt{0,5 \cdot \left[1 + \alpha_c \left(\bar{\lambda}_{fi,0} \cdot \sqrt{ky, q\,max / kE, q\,max} - 0,2 \right) + \bar{\lambda}_{\theta max}^{\ 2} \right]^2 - \bar{\lambda}_{\theta max}^{\ 2}}} \right) / 1,2 \right] \cdot A \cdot k_{y,\theta max} \cdot f_y}{1,0}$$

4.2.6.8 Reduction factors for the stress-strain relationship

The reduction factors k_θ for stress-strain relationship of structural steel at elevated temperatures are defined in [36] (Table 3.2). The relationship can be approximated by an exponential interpolation according to [40]:

$$k_{y,\theta} = \frac{1{,}0087}{\left(e^{\left(\frac{\theta-482}{39{,}19}\right)} + 1\right)^{0{,}2609}} \qquad \text{[40] (2b)}$$

In the same way a solution was found for the E-modulus that is very well valid for a temperature range of 400°C to 750°C. The values are on the save side for temperatures under 400°C and over 750°C (The development of a better fitting curve is planed).

$$k_{E,\theta} = \frac{1}{\left(e^{\left(\frac{\theta-455}{35}\right)} + 3{,}3\right)^{0{,}28}}$$

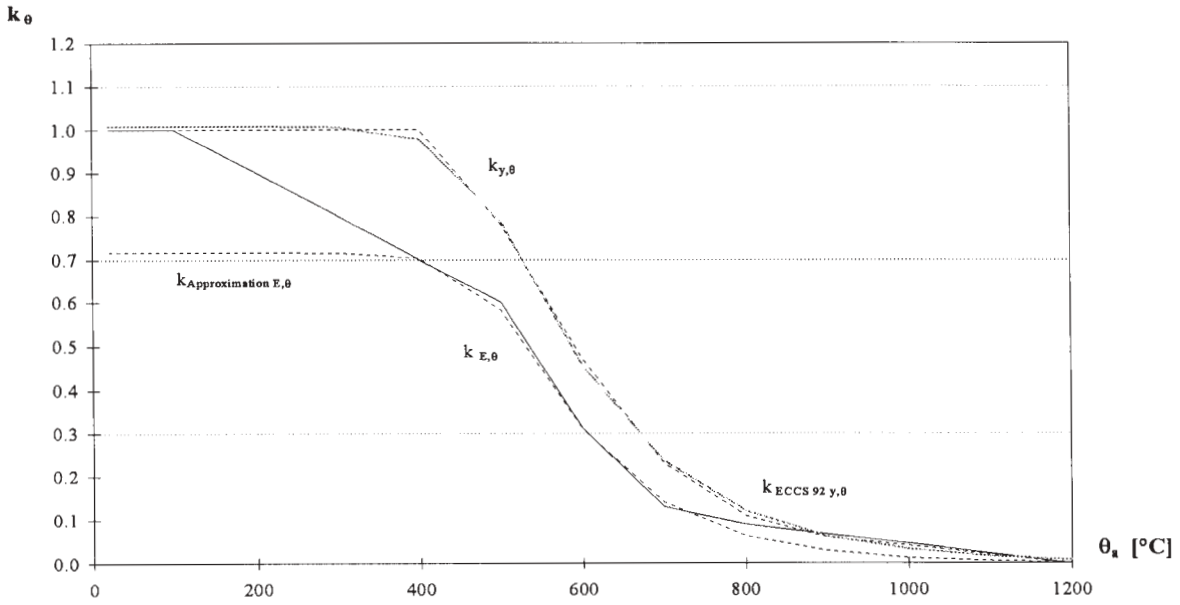


Figure 4.6: Reduction factors k_θ for stress-strain relationship of structural steel at elevated temperatures

4.2.6.9 Probability density function (PDF) for each variable (case of fire)

Self weight [29], [30], [24]:

P: law: Gaussian
nominal value : 50% fractile = 2000 kN
$V_Q = 0,1$
$m_Q = 2000$ kN
$\sigma_Q = m_Q * V_Q = 200$ kN

Variable load [29], [30], [24]:

N: law: Gumbel Type I
nominal value : 95% fractile = 2000 kN
$V_N = 0,3$
$m_N = 2000$ kN/1,56 = 1282,0
$\sigma_N = m_N * V_N = 384,61$

Structural steel:

R: law: lognormal
nominal value : 95% fractile = 235 N/mm²
$V_R = 0,052$ [30] (Table 2.3)
$m_R = e^{1,645VR} * 235$ N/mm² = 255,987 [30] (2.5)
$\sigma_R = m_R * V_R = 13,3$

Fire load:

q: law: Gumbel Type I
nominal value : 80% fractile = 560,0 MJ/m² [38], [1] Annex D
$V_N = 0,3$
$m_N = 560,0/1,3 = 430,0$
$\sigma_N = m_N * V_N = 130$

4.2.6.10 Limit state function including the massivity factor $A_m/V=16$

With a fitted relation of the maximum steel temperature as a function of the fire load the limit state function for each column can be found[1]. For a column ∅ = 250 mm according to chapter 5.

∅ = 250 mm A = 49087,4 mm² $A_m/V = 16,0$
I = 191,7476*10⁶ mm⁴
i = 62,5 mm

and the limit state function G:

[1] C. Fetz, VAP calculation, Column 13, April 1998

G = (((1/((0,5*(1+0,49*(((lk/i/(PI*((E/fy)^0,5)))*(((1/(0,9674*(1+EXP((TEMP-482)/39,19))))^(1/3,833)/(1/(((EXP((TEMP-455)/35))+3,3)^0,28)))^0,5))-0,2)+((lk/i/(PI*((E/fy)^0,5)))*(((1/(0,9674*(1+EXP((TEMP-482)/39,19))))^(1/3,833)/(1/(((EXP((TEMP-455)/35))+3,3)^0,28)))^0,5))^2))+((0,5*(1+0,49*(((lk/i/(PI*((E/fy)^0,5)))*(((1/(0,9674*(1+EXP((TEMP-482)/39,19))))^(1/3,833)/(1/(((EXP((TEMP-455)/35))+3,3)^0,28)))^0,5))-0,2)+((lk/i/(PI*((E/fy)^0,5)))*(((1/(0,9674*(1+EXP((TEMP-482)/39,19))))^(1/3,833)/(1/(((EXP((TEMP-455)/35))+3,3)^0,28)))^0,5))^2))^2-((lk/i/(PI*((E/fy)^0,5)))*(((1/(0,9674*(1+EXP((TEMP-482)/39,19))))^(1/3,833)/(1/(((EXP((TEMP-455)/35))+3,3)^0,28)))^0,5))^2)^0,5))/1,2)*A*fy/ 1000*(1/(0,9674*(1+EXP((TEMP-482)/39,19))))^(1/3,833)) - (N+P)

TEMP is the maximum steel temperature as a function of the fire load q. The equations of chapt. 4.2.6.6 are used for the heating curve. Here for the column
$\varnothing$ = 250 mm.
θ_{max} = TEMP = $-2*10^{-11} \cdot q^4 + 2*10^{-7} \cdot q^3 - 0{,}0005 \cdot q^2 + 0{,}9244 \cdot q + 59{,}437$.

With the VAP programm using the PDF's of all variables as input for the limit state function, the target probability can be obtained.

	nominal	fractile	m	σ	V	Law
P	2000	50%	2000	200	0,1	N
N	2000	95%	1282,05	384,62	0,3	GL
R	235	95%	255,987	13,3	0,052	LN
q	**560**	80%	430	130	0,3	GL

Table 4.4 Summary of the variables

Variables of G:

A	D	4,909e+04	
E	D	2,100e+05	
N	GL	1,109e+03	0,003
P	N	2,000e+03	200,000
f_y	LN	5,544	0,052
i	D	62,500	
l_k	D	2,000e+03	
q	GL	371,493	0,010

FORM Analysis of G:

$\varnothing$ = 250 mm β = HL - Index = 2,67 p(G<0) = 0,00378

Name	Alpha	Design Value
N	0,127	1,343 e+03
P	0,065	2,035e+03
f_y	-0,049	253,900
q	0,989	927,454

For a comparison a crude Monte Carlo Analysis of G was performed with 1'000'000 samples:

mean = 5592 kN sdev = 1112 kN skew = -2,207 kurt = 10,87 p (G<0) = 0,00422

For the column a failure probability of 0,00378 was found for 1 Mio. Monte Carlo samples.

4.2.6.11 Summary and discussion of the results

The probability of failure can be calculated for different column diameters.

D [mm]	A/V	θ_{max} for q_{fire} = 560 MJ/m²	t (θ_{max}) for q_{fire} = 560 MJ/m²	β	$p_{failure}$	$\alpha_{fire\ load}$
470	8,5	301,4	77,8	not available	0	not available
450	8,9	310,7	76,9	not available	0	not available
400	10,0	335,0	74,6	not available	0	not available
350[2]	11,4	363,5	71,8	not available	0	not available
300[3]	13,3	398,2	68,5	4,69	$1,37*10^{-6}$	0,829
250[4]	16,0	441,0	64,4	2,67	0,00378	0,989
200[5]	20,0	492,9	59,4	1,97	0,02450	0,963
150[6]	26,7	557,9	53,2	-1,29	0,90100	0

Table 4.5: Failure probability

4.2.6.12 Gamma factors

The following table summarises the results obtained with VAP, making a reduction of the steel section from the reference case.

[2] C. Fetz, VAP calculation, Column 17, April 1998
[3] C. Fetz, VAP calculation, Column 16, April 1998
[4] C. Fetz, VAP calculation, Column 13, April 1998
[5] C. Fetz, VAP calculation, Column 14, April 1998
[6] C. Fetz, VAP calculation, Column 15, April 1998

mean resistance section	P (G < 0)	design fire load	alpha fire	N increase of failure probability	γ decrease of design fire load
∅ = 470	0	not available	not available		
∅ = 450	0	not available	not available		
∅ = 400	0	not available	not available		
∅ = 350	0	not available	not available		
∅ = 300	$1{,}37*10^{-6}$	1378,0	0,829		
∅ = 250	0,00378	927,5	0,989	1	1
∅ = 200	0,02450	729,2	0,963	6,5	0,786
∅ = 150	0,90100	408,6	0	Cold Design is relevant	

Table 4.6 Probabilistic results of the FORM method

We can see that for the case of having a fully engulfed office room a column with the dimension of ∅ = 200 mm ($p_{failure} = 0{,}0245$) would satisfy the target probability of (see chapter 4.2.2.2)

$$p_{target} = \frac{p_{accepted}}{p_{FRI} \cdot t_{building-lifetime} \cdot Area} = \frac{7{,}25 \cdot 10^{-5}}{0{,}4 \cdot 10^{-6}\ 50\,years \cdot 50\,m^2} = 0{,}0725$$

This means that the column design at room temperature (∅ = 230 mm) must not be changed due to fire.

We see that the fire load has a weighting factor a of 0,83 or more. As a simplification the fire load was taken as the only variable (α = 1,0). All the other loads, the material characteristics and the geometrical dimensions were chosen as deterministic values. The results of the VaP calculations are summarized in Table 4.6.

∅ [mm]	A/V	θ_{max}	t (θ_{max})	β	$p_{failure}$	$\alpha_{fire\ load}$
300	13,3	398,2	68,5	4,40	$5{,}45*10^{-6}$	1,0
250	16,0	441,0	64,4	2,37	0,00901	1,0
200	20,0	492,9	59,4	1,40	0,08040	1,0
150	26,7	557,9	53,2		1,0	1,0

Table 4.7: Failure probability with the fire load as the only variable parameter

A comparison of Table 4.5 and Table 4.6 shows that the results with the assumption that the fire load is the only non deterministic parameter, is on the safe side and fits well the results from Table 4.5.

4.2.7 CONCLUSION

	∅ [mm]	β	p_f	p_{target}
cold	230	4,62	$1,9*10^{-6}$	$7,25*10^{-5}$
fire $q = 560$ MJ/m^2 $t_{R\ ISO} = 54$ min A/V = 20	200	1,97	0,02450	0,0725
fire $q = 560$ MJ/m^2 $t_{R\ ISO} = 63$ min A/V = 16	250	2,67	0,00378	0,0725

The column ∅ = 230 as needed for cold design would lead to a more than sufficient fire safety level.

Even a column with the dimension of ∅ = 200 mm ($\beta = 1,97$, $p_{failure} = 0,02450$) would satisfy the target probability of $p_{failure} = 0,0725$ (The column with ∅ = 200 mm and $\theta_{crit} = 640°C$ has an ISO resistance of $t_{R\ ISO} = 54$ min).

The column designed for ISO R60 with a required ∅ = 250 mm has a failure probability of ($\beta = 2,67$, $p_{failure} = 0,00378$) ~ 20 times smaller than the p_{target}. For this office (with A = 50 m^2, $\Gamma = 1,0$) the R60 requirement would therefore be too severe. As the probability of fire occurrence increases with office size it would even satisfy an office with 1000 m^2 surface area.

The chosen time temperature curve is very severe (small opening factor of 0,04) leading to temperatures similar for the ISO fire. In modern offices opening factors of 0,15 to 0,35 are found leading to lower temperatures and fuel bed controlled fires, hence even smaller failure probabilities.

We can see that for the column ∅ = 250 mm (including the massivity factor of $A_m/V = 16,0$) the critical temperature of 640°C is reached by a fire load of about 1016,5 MJ/m^2 (see Figure 4.5).

By taking into account a sprinkler system p_{target} would increase to 0,0725 / 0,02 = 3,625 > 1,0. This means that no fire resistance is needed if a sprinkler system is present for our example (office with 50 m^2 and sprinkler).

The Table 4.6 shows the γ_n as a function of the increase of failure probability N. It shows similar values than the Table D of chapter 4.1 (for $\beta = 2,37$: Table D: $\gamma_n = 0,7$ for N = 10 and Table 4.6: $\gamma_n = 0,786$ for N = 6,5).

4.3 PROTECTED STEEL BEAM

4.3.1 INTRODUCTION

In order to define a possible reduction of protection of steel section due to active measures, we need to determine the steel section with or without protection which satisfies the target probability value.

Without taking into account any active measures leading to a reduction of fire occurrence, two cases can be used for satisfying the target probability :

- define the protection of the steel section determined at room temperature,
- define a steel section which is in lot of cases non realistic but used as a reference.

According to this, we have applied the both approaches. When the target probability is reached and the reference case is defined, the effect of active measures can be quantified.

4.3.2 STUDIED CASES

4.3.2.1 Compartment and fire load

It has been chosen an office as the compartment. The surface of this office is $50m^2$. The distribution of fire load in this compartment is, assuming a Gumbel distribution, given by the two following figures.

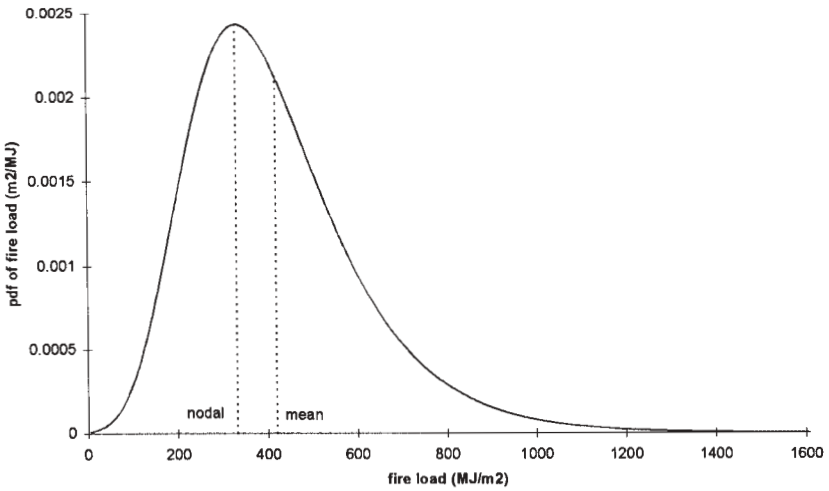


Figure 4.7 : PDF of fire load density in office

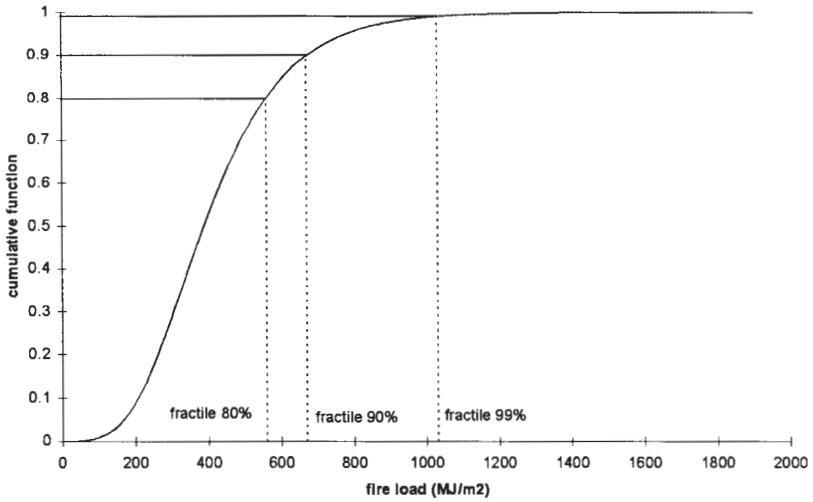


Figure 4.8 : Cumulative distribution of fire load in office

This PDF of fire load in office corresponds to the following statistic values [42] (the values of the final WG4 report are slightly different):

- mean value : 420 MJ/m^2
- standard deviation : 194 MJ/m^2
- nodal value : 332 MJ/m^2
- fractile 80% : 560 MJ/m^2
- fractile 90% : 670 MJ/m^2

4.3.2.2 Target probability

Before any calculations, the target probability has to be defined :

According to EC1 part 1 [24], a target probability of failure risk is 7,25 10^{-5} /building life.

Considering the probability of having a fully engulfed compartment (according to a previous draft of the WG3 report) of 5 10^{-7} /m^2/year, and a building life of 50 years, so

$p_t = 25\ 10^{-6}$ /m^2/building life

and according to the fire compartment surface, the probability to have a fully engulfed fire in such compartment is : 12,5 10^{-4} / building life

In such case, the target probability of failure risk is :

$P_{t,fi} = 7{,}25\ 10^{-5} / 12{,}5\ 10^{-4} = 0{,}058$

4.3.2.3 Calculations procedure

The following different steps have been considered in order to make calculations :

- Calculations with OZONE with variations of the fire load and using the combustion model n°2,
- Calculations of unprotected steel temperature for each OZONE calculations,
- Definition of the relation between fire load and maximum steel temperature,
- Definition of the limit state function for a beam for which the static loads are chosen,
- Determination of the steel section using the VAP program satisfying the target probability.

This steel section became then the reference steel section.

Other details of this procedure are also shown in the paper of D. Joyeux [46] .

4.3.3 APPLICATION : CALCULATION OF THE REFERENCE SECTION FOR THE STUDIED CASE

4.3.3.1 Definition of the limit state function

4.3.3.1.1 Relation between fire load and maximum steel temperature

After having realised calculations with ozone, values of maximum unprotected steel temperature have been obtained as function of fire load. The compartment is defined by an opening factor of 0,04 a surface area of 50 m^2 and a height of 3,4 m. A relation has been defined for a best approximation. The comparison is shown in Figure 4.9. In this figure is also shown the temperature-fire load relationship defined by L.G. Cajot [47] using the maximum temperature of the parametrical fire curves [48] or of the ISO-fire.

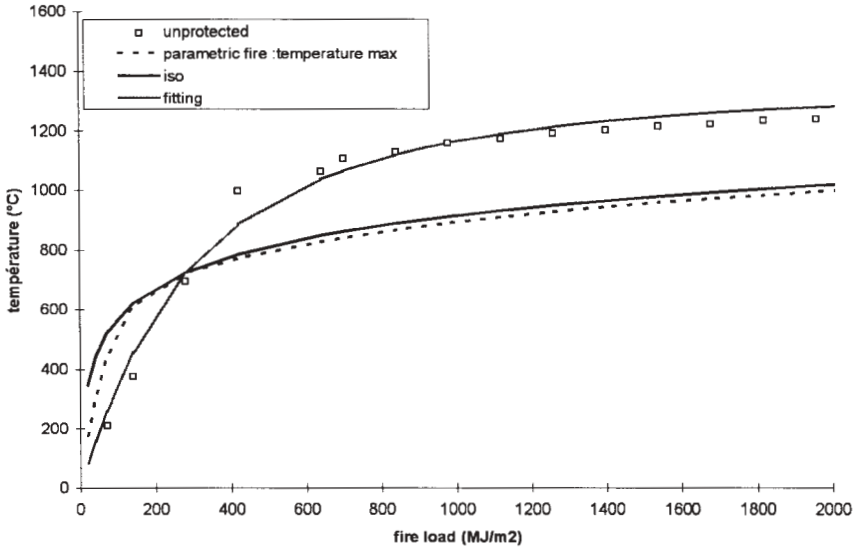


Figure 4.9 : Relationship between unprotected steel temperature and fire load

The best fitting curve has been defined as the following relation :

$$T_{max}=1325^{*}\left(1-0{,}324\exp\left(-0{,}002Q_f\right)-0{,}204\exp\left(-0{,}001Q_f\right)-0{,}472\exp\left(-0{,}005Q_f\right)\right) \quad (1)$$

We will consider that this relation obtained with a steel profile HE 200B is independent on the massivity factor.

4.3.3.1.2 Limit state function

According to this relation between the maximum steel temperature and the fire load, it can be defined the limit state function. The relation is relative to an isostatic beam for which a characteristic permanent load of 20 kN/m and characteristic imposed load of 25 kN/m is used.

The corresponding limit state function, considering the reduction factor versus temperature defined as Eurocode 3 part 1.2, is the following :

G = (1/(0,9674*(1+exp((1325*(1-0,324*exp(-0,002*q_f)-0,204*exp(-0,001*q_f) -0,472*exp (-0,005*q_f))-482)/39,19))))^(1/3,833)*R-(P+Q)*L^2/8 (2)

where :

P the permanent load
G the imposed load
R the resistance
q_f the fire load
L the length of the beam

4.3.3.2 Probability density function

The probability density function (pdf) of each variable has to be defined :

* Permanent load P :
  As it is defined in Eurocode 1 part 1, the probability is a Gaussian curve determined such as the characteristic value is the mean value and the variance is equal to 0,1.
* Imposed load Q :
  A Gumbel type 1 is used and the characteristic value represents a 95% fractile of the distribution and the variance is equal to 0,3. With such values, the average value is 16 kN/m and the standard deviation is 4,8 kN/m
* Resistance R :
  The characteristic value R_c of the resistance is equal to a 95% fractile and the variance is 0,052.
* Fire load q_f for office :
  The Gumbel distribution is used with a mean value of 420 MJ/m^2 and a standard deviation of 194 MJ/m^2.
* Length of the beam L :
  L is taken as a deterministic value 8 m.

4.3.3.3 Reference section

With the VAP program [33] , according to the different PDF, and the limit state function, it can be obtained the section which satisfies the target probability.

The following case reaches the target probability :

Resistance :

- mean value : 3950 kNm
- variance : 0,052 leading to a standard deviation of 205,6 kNm

Such PDF leads to a characteristic value of : 3627 kNm

The design values and the alpha coefficient corresponding are the following :

FORM Analysis of G:

HL - Index = 1,58 P(G<0) = 0,0569

Name	Alpha	Design Value
P	0,120	20,381
Q	0,310	17,519
R	-0,120	3,911e+03
qf	0,936	730,651

According to such results, it appears that an increased factor, coming from the design value of fire load (730 MJ/m^2, corresponding to 93% fractile) and the characteristic value (chosen in semestrial report as a 80% fractile) of 560 MJ/m^2, is 1,3.

The resulting steel section is necessarily far from a steel section defined at room temperature of 581,6 kNm, because without any active or passive measures in such compartment, it is difficult to satisfy a fire stability.

4.3.3.4 Gamma factors

In order to satisfy the target value, it has to be defined either a protection, or a reduction of fire probability occurrence due to active measures.

According to the protection, similar calculations have to be made with a limit state function taking into account a protected steel temperature as a function of fire load as it is defined by D. Joyeux in the reference paper INC-97/465- DJ/IM [46] .

For the active measures, it can be determined the reduction of steel section according the increase of the target probability. Such calculations can define the relation between design fire load reduction and failure probability increasing regards to the reference case. The following table summarises the results obtained with VAP, making reduction of the steel section from the reference one.

mean resistance section	P(G<0)	design fire load	alpha fire load	R design	increase of failure probability	decrease of design fire load
3950	0,058	730	0,936	3911	1	1
3500	0,0957	657	0,938	3472	1,679	0,9
3000	0,169	574	0,942	2982	2,96	0,78
2500	0,29	488	0,945	2492	5,08	0,668
2000	0,474	399	0,95	1999	8,31	0,546
1000	0,905	207	0,969	1006	15,9	0,283
633	0,98	131	0,98	638	17,19	0,179
500	0,991	101	0,984	507	17,38	0,134
100	0,5	388	2 10-9	100	8,8	0,5315

Table 4.9 : Probabilistic results of the FORM method

According to this table the inverse coefficient of failure probability divided by the target probability of the reference case can be calculated and is shown versus the gamma factor reduction of the design fire load, in the Figure 4.10a. This figure is valid for the reference case corresponding to P (G<0) = 0,058 or to β_{fi} = 1,57.

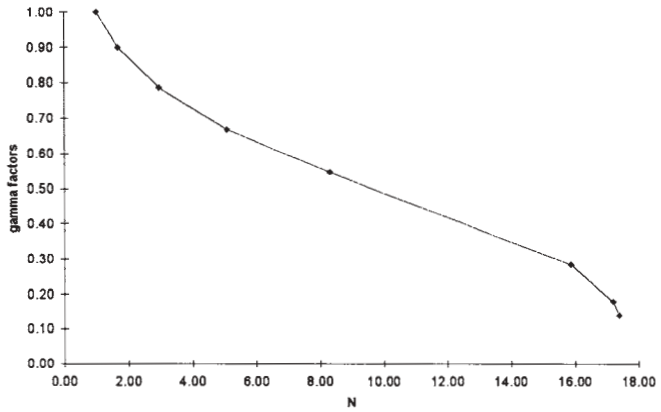


Figure 4.10a : Gamma factors on design fire load versus probability increase

In this figure, it does not appear the last value of steel section resistance of 100 kNm, because this steel section is too low, and the fire load becomes not important load, as it can be seen on the alpha value of 2 10^{-9}. Such section does not satisfy the criteria at room temperature. The design values of the static loads are then modified.
In order to see the corresponding fractile of the design fire load, the increase of probability is shown versus the fractile of fire load of the design value in the following Figure 4.10b. The fractile coming from the design fire load is determined from the cumulative distribution of the fire load (see Figure 4.8).

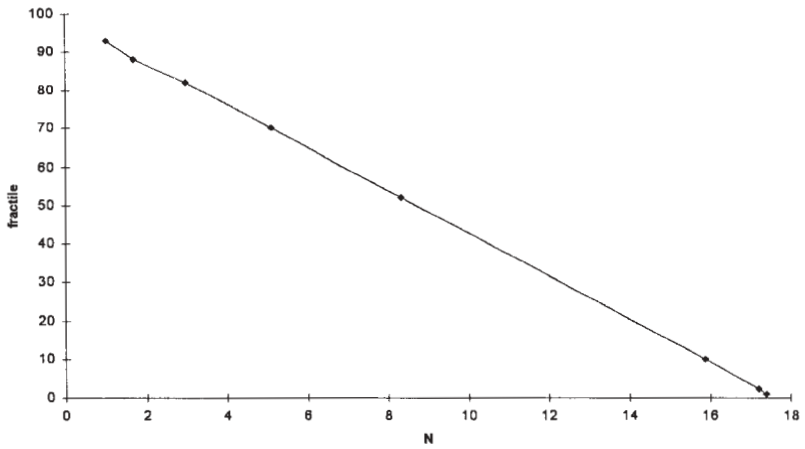


Figure 4.10b : Design fractile of fire load versus probability increase

Such curve is very interesting, because it shows that there are :

- a rather linear relation between N and the fractile,
- the fractile tends to 100% when the probability reduction tends to zero,
- the fractile tends to 0 when the probability reduction tends to about 17,5 (corresponding to the inverse of the target probability of 0,058 - see 4.3.2.2).

4.3.4 APPLICATION : CALCULATION OF THE REFERENCE INSULATION THICKNESS FOR THE STUDIED CASE

A similar procedure of calculations can be made with a variation of the insulation thickness.

4.3.4.1 Definition of the limit state function

4.3.4.1.1 Relation between fire load and maximum steel temperature

After having realised calculations with ozone, values of maximum protected steel temperature have been obtained as function of fire load. The considered compartment is the same as the compartment used in chapter 4.3.3. The first calculations have been performed with one insulation thickness 20 mm, based on vermiculite. A relation has been defined for a best approximation :

Temperature of insulated steel with 20 mm of vermiculite :

$$T_a = 875\log\left(0{,}2q_f^{0,7}\right) + 500\left(1 - \exp\left\{-\frac{10000}{q_f}\right\}\right) + 200\left(1 - \exp\left\{-\frac{q_f^3}{2500^3}\right\}\right) - 980 \qquad (3)$$

Such relation is shown in the following figure :

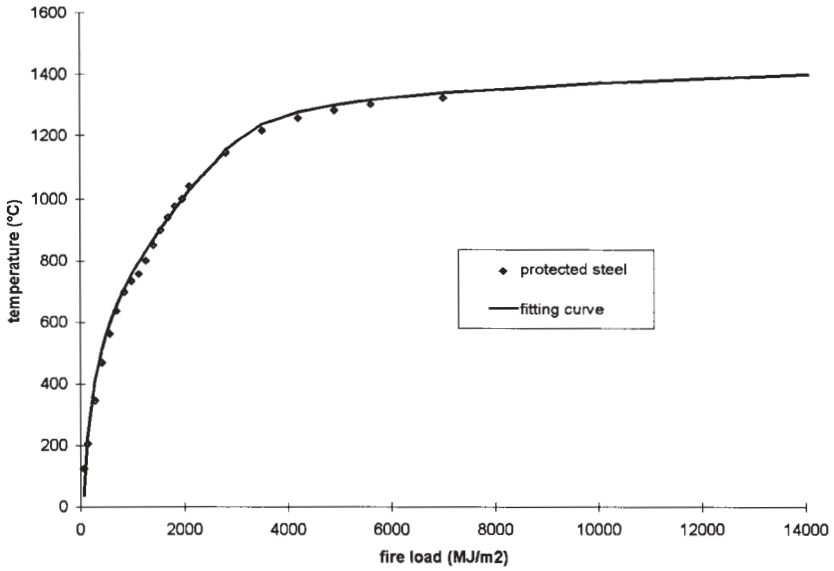


Figure 4.11 : Protected steel temperature versus fire load density

In order to take into account the effect of the insulation thickness, a parametric study of the massivity factor and insulation thickness has been made with one case of fire load.

The resulting curves of maximum steel temperature versus massivity factor and insulation thickness are the following :

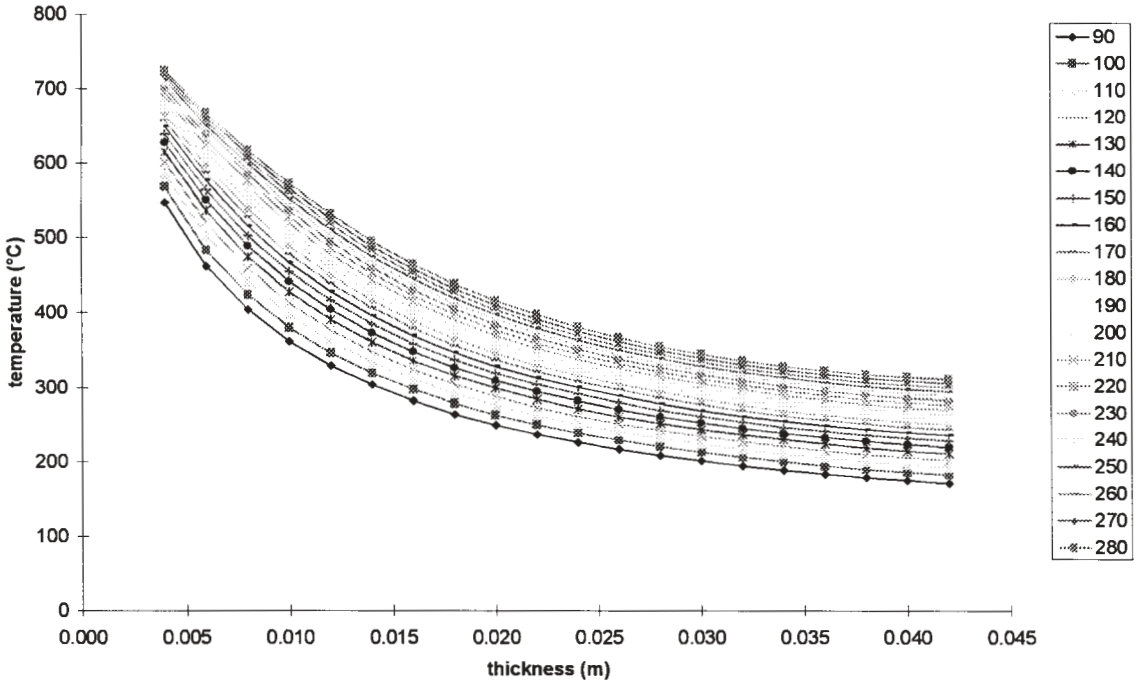


Figure 4.12 : Relationships between maximum steel temperature, massivity factor, and insulation thickness

Coming from such curves, a relation has been built. This relation has been obtained as an adimensional system based on the value with a thickness of 20 mm and a massivity factor of 150.

Thus the maximum steel temperature is deduced from the following relation :

$$T(AsV, Ep)=T(150, 0{,}02)^{*} LOG(AsV/15) * \exp^{((0{,}02^{0,4}-Ep^{0,4})/0{,}15)} \quad (4)$$

where :

$A_s V$ is the massivity factor (m^{-1})
Ep the insulation thickness (m)
$T(A_s V, E_p)$ the maximum steel temperature depending on these two parameters

The equation (4) gives the curves of the maximum steel temperature versus massivity factor and insulation thickness, of the Figure 4.13, which are rather close to the curves of the Figure 4.12.

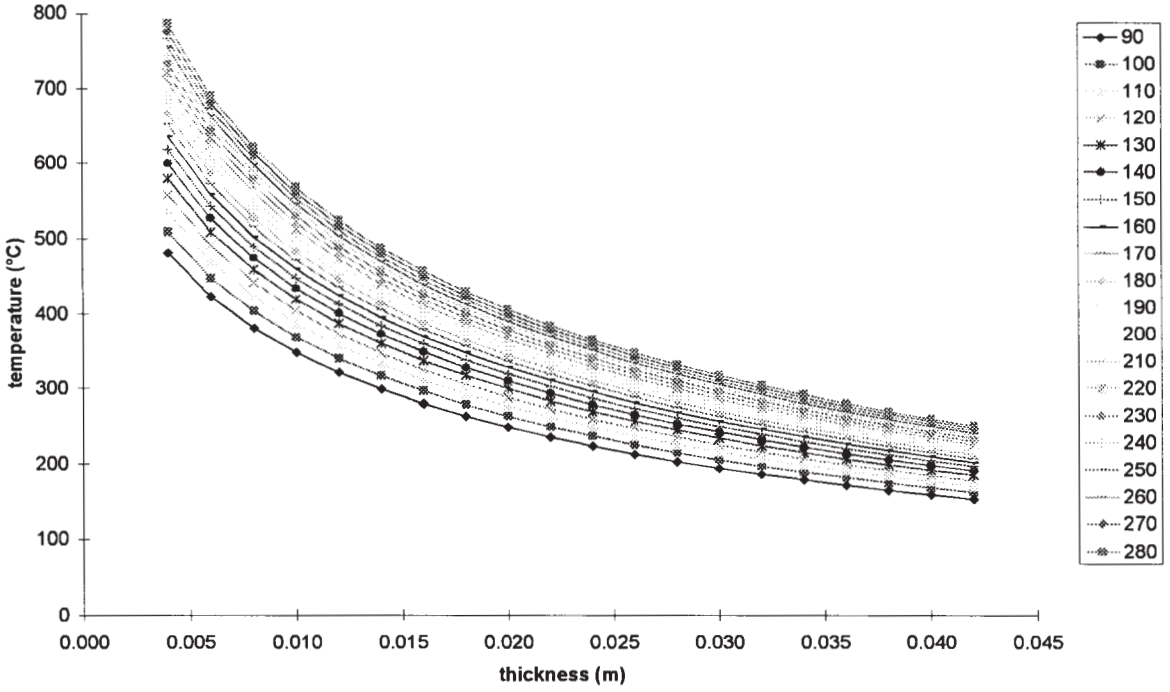


Figure 4.13 : Relationships between maximum steel temperature, massivity factor, and insulation thickness

The combination of equations (3) and (4) gives the resulting temperature depending on the three variables :

- q_f : the fire load (MJ/m^2)
- $A_s V$: the massivity factor (m^{-1})
- E_p : the insulation thickness (m^{-1})

4.3.4.1.2 Limit state function

According to the temperature relationship, and the Limit state Function depending on :

- the Fire load q_f,
- the length of the beam L ,
- the permanent load P,
- the static load Q,
- the resistance R,
- the insulation thickness E_p,
- The massivity factor A_sV,

is the following :

G = (1/(0,9674*(1+exp(((875*ln(0,2*qf^0,7)/ln(10)+500*(1-exp(-10000/qf))+200*
(1-exp(-qf^3/2500^3))-980)*ln(ASV/15)/ln(10)*exp((0,02^0,4-
EP^0,4)/0,15)482)/39,19))))^(1/3,833)*R-(P+Q)*L^2/8

4.3.4.2 Probability Density function

The distribution of the different loads is exactly the same as defined in §4.3.3.2. The insulation thickness and the massivity factor are defined as a deterministic distribution with a single value.

4.3.4.3 Reference insulation thickness

Different calculations with the program VAP and the FORM method have been performed in order to find the insulation thickness which satisfies the target probability value of 0,058. The reference case of the resistance of the section is defined at room temperature [47].

The target value is obtained with an insulation thickness of 25 mm.

The results of VAP are the followings :

Variables of G:

A_SV	D	150,000	
EP	D	0,025	
L	D	8,000	
P	N	20,000	2,000
Q	GL	13,840	0,267
R	LN	6,450	0,052
q_f	GL	332,690	0,007

FORM Analysis of G:

HL - Index = 1,61 P(G<0) = 0,054

Name	Alpha	Design Value
P	0,082	20,264
Q	0,199	16,669
R	-0,079	628,502
q_f	0,973	756,582

A design value of the fire load is 756 MJ/m^2, which corresponds to a fractile of 94 %.

4.3.4.4 Gamma factors

The same procedure as used in case of section decrease (§4.3.3.4) is used to define the gamma factors applied on the design fire load for decrease the insulation thickness. So calculations of failure probability have been made with reduction of the insulation thickness. This last variable is the single one that has been modified in the calculations with the FORM method.
The following table summarises the results :

insulation thickness	P(G<0)	design fire load	alpha fire load	R design	increase of failure probability	decrease of design fire load
0,025	0,054	756	0,973	628	1	1
0,024	0,071	716	0,975	628	1,315	0,947
0,022	0,117	640	0,978	629	2,167	0,846
0,020	0,183	570	0,98	630	3,389	0,754
0,018	0,267	507	0,983	631	4,944	0,670
0,016	0,368	449	0,985	632	6,815	0,594
0,014	0,48	396	0,988	632	8,889	0,524
0,012	0,593	349	0,99	633	10,981	0,462
0,010	0,698	306	0,992	633	12,926	0,405
0,008	0,789	266	0,994	633	14,611	0,352
0,006	0,862	230	0,996	633	15,963	0,304
0,004	0,916	195	0,997	633	16,963	0,258

Table 4.10 : Probabilistic results with the FORM method

According to this table the inverse coefficient of failure probability divided by the target probability of the reference case can be calculated and is shown versus the gamma factor reduction of the design fire load in the Figure 4.14.

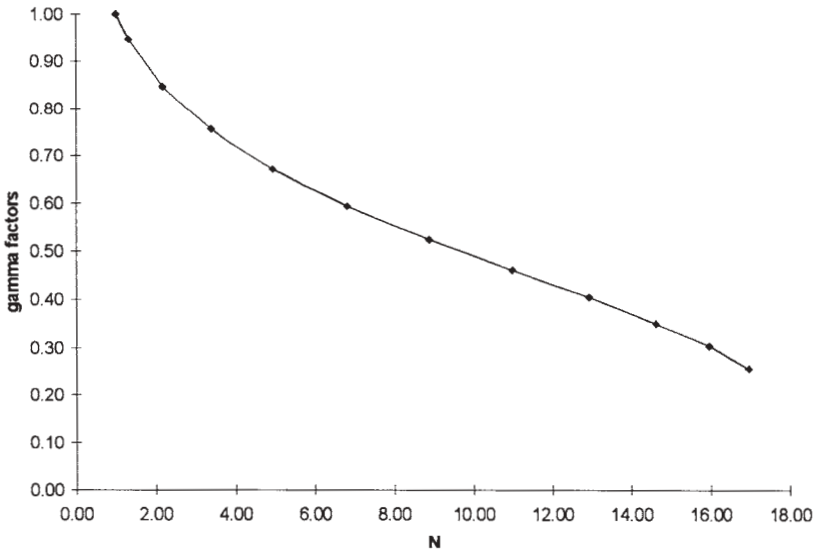


Figure 4.14 : Gamma factors on design fire load versus probability increase

In order to see the corresponding fractile of the design fire load, the increase of probability is shown versus the fractile of fire load of the design value in the Figure 4.15.

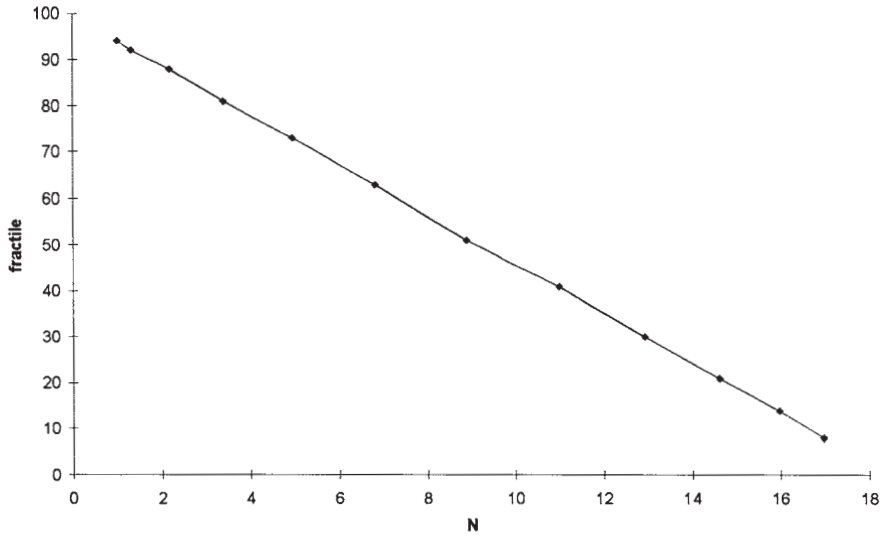


Figure 4.15 : Design fractile of fire load versus probability increase

Similar results as the unprotected steel calculations, are obtained. The results of the two procedures (variation of section or of insulation thickness) are compared in the following paragraph.

4.3.5 COMPARISON

Two methodologies have been used to define the gamma factors applied on the design fire load :

- variation of the steel section,

- variation of the insulation thickness.

The first methodology using the steel section is in most of cases unrealistic. Sometimes, when a small increase of the section allows unprotected steel, this procedure is used.

The second one is the procedure generally applied to satisfy the requirements on structural fire stability.

In both methodologies, a reference is defined (a steel section or an insulation thickness) which satisfies the target probability. Coming from the reference, the variables (steel section, or insulation thickness) is reduced, leading to an increase of the failure probability and reduction of the design fire load. Assuming that the calculated failure probability is in each case a new target probability due to reduction with active measures, it can be defined a reduction of the design fire.

Such assessment has been made for the both methodologies : gamma factors versus probability reduction. The following figure shows the comparison.

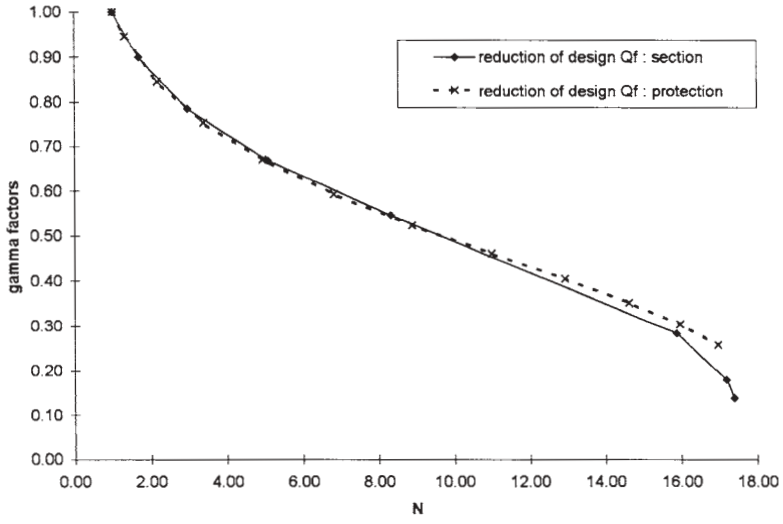


Figure 4.16 : Gamma factors versus probability reduction with both methodologies

These results show that a single curve can be deduced considering any methodology. It seems that only one parameter appears : the maximum probability reduction N depending on the target probability (inversely proportional), which depends on the compartment.

It has been shown a linear relation between the design fractile of fire load, and the probability reduction. The Figure 4.17 shows the design fractile versus probability reduction in both methodologies. One can remark a rather similar curve.

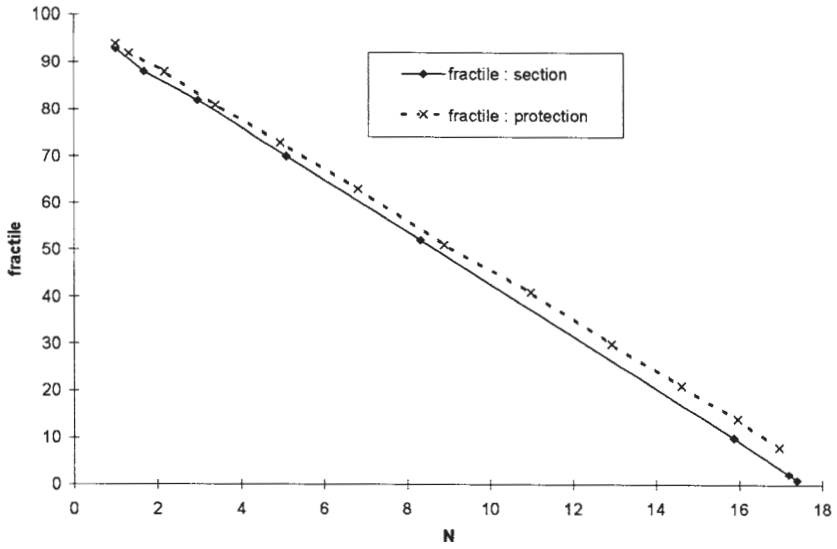


Figure 4.17 : Design fractile of fire load versus probability reduction

Such comparison shows that the results are independent on the methodology.

One can also remark that in case of protected steel section, for a reduction of the insulation thickness tending to zero, the failure probability and the design fire load tend to the values obtained without protection with a same resistance.

4.3.6 CONCLUSION

The methodology defining the reduction of design fire load because of active measures playing on the target probability has been defined.

A linear decrease of the design fractile of fire load is observed versus the fire probability reduction N.

The γ_{qf} on the fire load versus the failure probability increase is given on the Figures 4.10a and 4.16. It corresponds to a reference case with a β_{fi} of 1,57.

4.4 PROTECTED STEEL COLUMN

The case has been dealt with in the scope of the analysis of a real example "The Office Building Langenthal".

This example is provided in Annex C

5. ACCEPTANCE CRITERIA FOR STRUCTURAL FIRE RESISTANCE

In this report (see chapter 3.1) and in the whole NFSC approach, the assumption of **a target failure probability p_t of $7{,}23.10^{-5}$ per building life or $1{,}3.10^{-6}$ per year** (sometimes $7{,}25.10^{-5}$ has been used) as defined in ENV 1991-1 [24] has been considered.

This means that the safety requirement (β>3,8) for ultimate limit state in **normal** conditions has also been adopted as the acceptance criteria for the structural **fire** resistance. The required safety in case of fire could be reduced. This idea has been developed in the Annex B.

In chapter 2.8 of the Annex B, it is proposed to use a target failure probability depending on the people evacuation.

$p_t = 1{,}3 \cdot 10^{-4}$ for normal evacuation p_t [1/year]
$p_t = 1{,}3 \cdot 10^{-5}$ for difficult evacuation (hospitals, etc.)
$p_t = 1{,}3 \cdot 10^{-6}$ for no evacuation.

That has not been included in the NFSC approach. It might lead to future interesting improvements but it was decided to keep the value of ENV 1991-1 accepted by everybody whereas discussions should be needed to convince the Authorities to adopt new target values.

6. CONCLUSION -DIFFERENTIATION FACTOR γ_{Q1}, γ_{Q2} AND γ_{QN}

The fire is considered as an accidental action. This accidental action can occur with a probability p_{fi} depending on the type of occupancy, of the fire compartment area and on the fire fighting active measures. The effect of the fire depends on some parameters.

In buildings the most relevant parameter is the fire load.

The aim of the WG5 was to establish the methodology to provide the design values of the fire parameters (mainly fire load) which take into account the fire probability. These design values are then used by the tool developed by WG1 (OZONE) to calculate the design natural fire curve.

In a first step the existing methods considering the active fire fighting measures have been analysed. Amongst these methods, the DIN 18230 [2 ,4, 5] had already been based on some statistical considerations. The background of the DIN 18230 has been analysed and is described in Annex A of this report.

Afterwards the Annex A of ENV 1991-1 [24], which describes the semi-probabilistic concept leading to the **design** values for the actions and for the materials properties, has been extended to the structural fire resistance.

The safety factors γ for the actions and the material properties has been deduced by a semi-probabilistic approach (Annex A of ENV 1991-1) which assumes implicitly that the failure probability of the structure p_f is lower than a target failure probability of $7{,}23.10^{-5}$ per working life of the building, which is equivalent to a safety factor β of 3,8 :

$$p_f \text{ (failure probability)} \leq p_t \text{ (target probability)} \quad (6.1).$$

In case of fire, the main action is the fire which can be quantified by the fire load expressed in kg of wood or in MJ. However, this fire load becomes a real action for the structure only when there is a fire. The fire load influences really the structure only with a certain probability p_{acc}, p_{acc} being the product of p_1 (probability that a fire starts) and p_2 (probability that this starting fire turns to a flash-over or a fully engulfed fire compartment).

In case of fire which is considered as an accidental action the equation (6.1) becomes p_f (failure probability in case of fire) * p_{acc} (probability of fire) $\leq p_t$ (target probability). In that way the safety index β_{fi} has to be determined by using $p_{t,fi}$ which is equal to (p_t /p_{acc}) and enables us to determine the corresponding safety factor γ_{qf} for the fire load.

This factor has been divided into subcoefficients γ_{q1}, γ_{q2}, γ_{ni} to take into account the compartment size, the building type and the different active fire fighting measures like sprinklers.

The annex A of ENV 1991-1 [24] assumes also that the weighing factor α for the main action, here the fire load is equal to –0,7. The γ_{q1}, γ_{q2}, γ_{ni} defined in the chapter 3.3 are based on this value of –0,7 for the weighing factor α_q of the fire load.

In order to verify this assumption, reliability calculations described in chapter 4 for different types of structure have been performed. These calculations show that the value of the weighing factor α for the fire load is in fact closed to (-0,9).

The Figures 3.6 and 3.7 of the chapter 3 becomes then the following Figures 6.1 and 6.2 which attest that the γ_{ni} can be even smaller than the ones deduced in chapter 3 (Table 3.3). Moreover the VAP calculations (see Table D of chapter 4.1 for unprotected steel beam, the Table 4.7 for unprotected steel column and Figures 4.10a and 4.14 for protected steel beam) prove that the γ_{ni} can be reduced again.

All these calculations have been presented and discussed with the Advisory Committee. According to this report, to the comments of the Advisory Committee and to the works made in the scope of the ECSC project N°7215-PA/PB/PC-042 "Valorisation Project - Competitive Steel Buildings through Natural Fire Safety Concept", the factors γ_{q1}, γ_{q2} and γ_{ni} given in the Figures 6.3, 6.4 and 6.5 have been adopted.

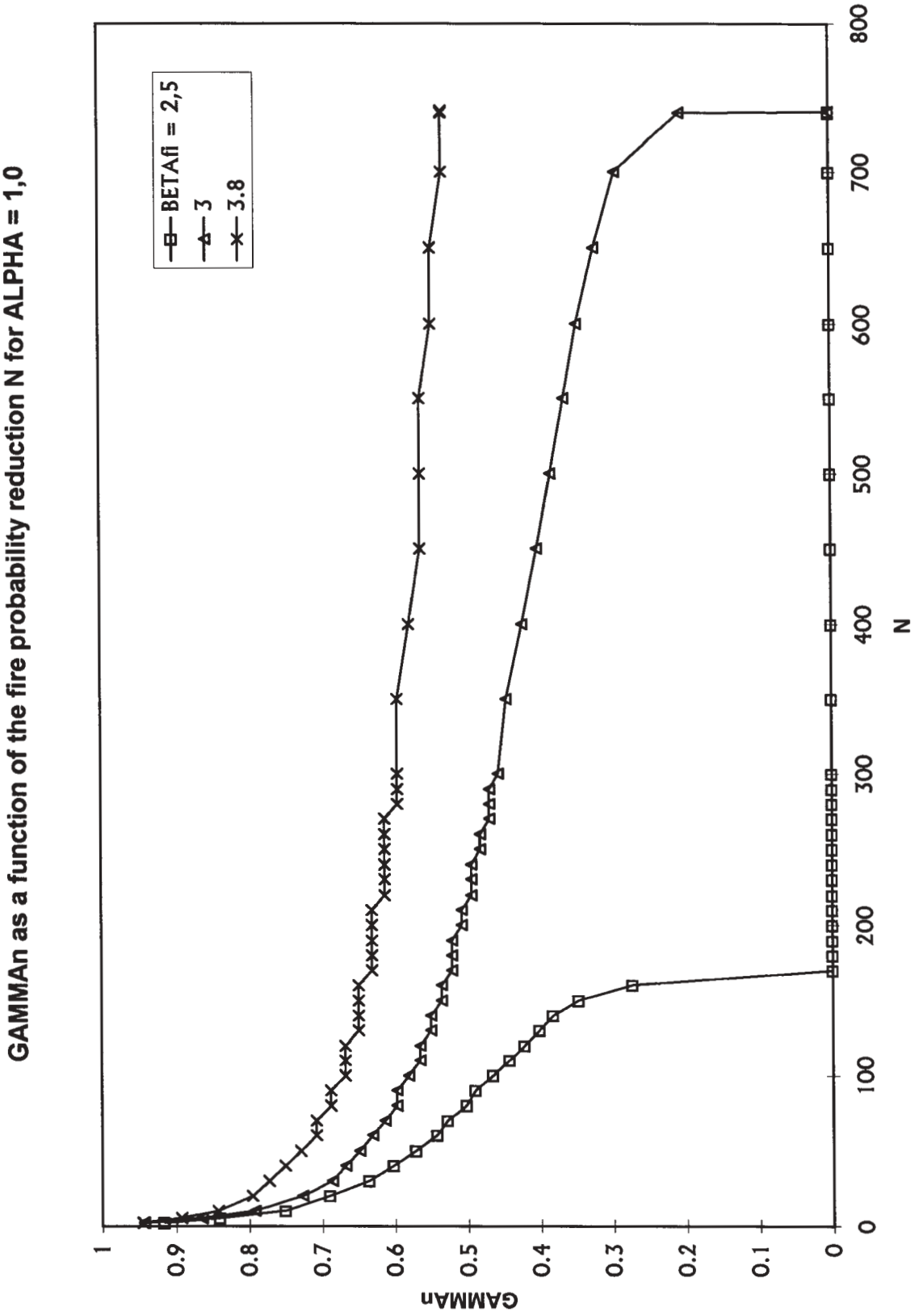

GAMMAn as a function of the fire probability reduction N for ALPHA = 1,0
BETAfi = 2,5
3
3.8
GAMMAn
N
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
100
200
300
400
500
600
700
800

Figure 6.1

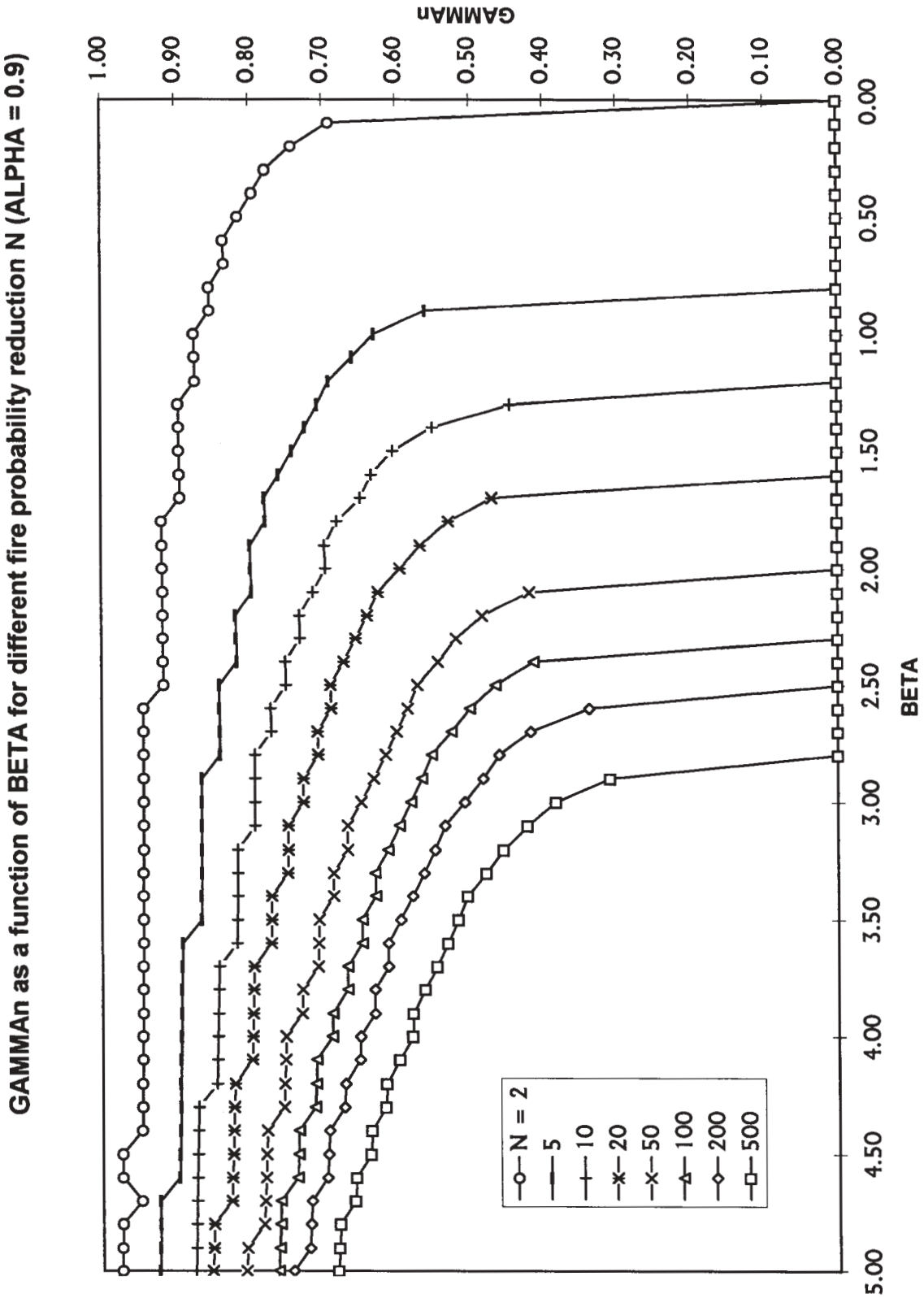

GAMMAn as a function of BETA for different fire probability reduction N (ALPHA = 0.9)
GAMMAn
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
BETA
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
5.00
N = 2
5
10
20
50
100
200
500

Figure 6.2

Compartment floor area A_f [m²]	Danger of Fire Activation γ_{q1}
25	1,10
250	1,50
2500	1,90
5000	2,00
10000	2,13

Figure 6.3

Danger of Fire Activation γ_{q2}	Examples of Occupancies
0,78	artgallery, museum, swimming pool
1,00	residence, hotel, paper industry
1,22	manufactory for machinery & engines
1,44	chemical laboratory, painting workshop
1,66	manufactory of fireworks or paints

Figure 6.4

	Active Measures	Fully Developed FIRE PROBABILITY REDUCTION	γ_{ni}
Automatic Suppression	Sprinkler (S)	50	0,61
	Sprinkler + 1 independent Water Supply	100	0,53
Manual Fire Suppression	Work Fire Brigade (WFB)	50	0,61
	Standard Fire Brigade (SFB)	10	0,78
	... + Automatic fire detection by heat by smoke	... 4 ... 16	... 0,87 ... 0,73
	... + Automatic Alarm Transmission to Fire Brigade	... 4	... 0,87

Figure 6.5

By comparison with the effect of other active measures, with other Standards and by discussions with the experts of the Advisory Committee, new factors γ_{ni} have been introduced to consider the independent water supplies in case of sprinklers and the normal fire fighting measures, which should be almost always present, such as the Safe Access Routes, the Fire Fighting Devices, and the Smoke Exhaust System. For these normal fire fighting measures, the γ_{ni} is 1,0 but becomes 1,5 if they have not been foreseen (see Figure 6.6).

Figure 6.6

Official Document		γ_{ni} Function of Active Fire Safety Measures										$\gamma_n^{min} = \gamma_{n1} \cdots \gamma_{n10}$ $\gamma_n^{max} = \gamma_{n4} \cdot \gamma_{n7}$
		Automatic Fire Suppression		Automatic Fire Detection			Manual Fire Suppression					
Title	Date of publication	Automatic Water Extinguishing System γ_{n1}	Independent Water Supplies 0 | 1 | 2 γ_{n2}	Automatic fire Detection & Alarm by Heat γ_{n3}	Automatic fire Detection & Alarm by Smoke γ_{n4}	Automatic Alarm Transmission to Fire Brigade γ_{n5}	Work Fire Brigade γ_{n6}	Off Site Fire Brigade γ_{n7}	Safe Access Routes γ_{n8}	Fire Fighting Devices γ_{n9}	Smoke Exhaust System γ_{n10}	
SIA 81	1984	0,50 / 0,59	/	0,83 or 0,69		0,83	0,67 or 0,63 $\gamma_{n6} \cdot \gamma_{n7} = 0,53$		/	1,0 / 1,39*	0,85	0,13 / 0,49
ANPI	1988	0,58 ⊙	1,0 | 0,86 | 0,65	0,82	0,68	included in ⊙	0,50	0,68	/	1,0 / 1,36*	/	0,07 / 0,48
DIN 18230-1	1987/98	0,60	/	0,90		/	0,60	/	/	/	/	0,32 / 0,54
ENV 1991-2-2	1995	0,60	/	/	/	/	/	/	/	/	/	0,60
NFSC PROPOSAL	1998	0,61	1,0 | 0,87 | 0,7	0,87 or 0,73		0,87	0,61 or 0,78		0,9 or 1 / 1,5*	1,0 / 1,5*	1,0 / 1,5*	0,15 / 0,57

* For normal fire fighting measures, which should be almost always present, such as the Safe Access Routes, the Fire Fighting Devices and the Smoke Exhaust System in staircases, the corresponding γ_{ni} should be taken as 1,5 in case those measures either are unsatisfactory either are not existing.

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ANNEXES

Annex A: Background of the DIN 18230 and Extension to other types of Buildings

Annex B: Acceptance criteria for structural fire resistance

Annex C: Office Building Langenthal

ANNEX A

Background of the DIN 18230 and Extension to other types of Buildings (see NFSC317 of Mr. Schweppe)

Synopsis. Based on the theoretical considerations of safety, a generalized concept for fire engineering design is presented, offering the possibility of applying DIN 18230 to buildings other than the previously restricted type of industrial buildings. After a short introduction to the theoretical background of safety factors in general the new safety concept is developed on the basis of occurrence and failure probabilities in the case of fire. The proposed method serves as a tool to create an individual fire engineering design for each building project. In each case structural boundary conditions and additionally provided fire safety measures can be realistically taken into account.

1 Introduction

According to paragraph 17 of the Landesbauordnung of North Rhine-Westphalia all types of buildings must be designed to prevent fire ignition and spreading of fire and smoke, so that the safety of people and animals can be guaranteed as well as enabling effective fire-fighting measures.

As a consequence, the Building Regulations of each German federal country and the special regulations for buildings of a particular kind and use - (e.g. offices, public buildings, high rise buildings, restaurants, hospitals, hotels, garages etc.) - have fixed special requirements for fire engineering like. These are, for example, fire compartments, the arrangement of firewalls and the combustibility of the materials used. The component parts are assigned to fire resistance classes according to ISO-fire conditions of DIN 4102, part 2 [1].

In industrial buildings the required fire resistance time can be calculated according to DIN 18230 on the basis of the Industriebaurichtlinie [3]. Hereby the local boundary conditions and the specific building properties can be considered realistically.

DIN 4102, part 4 [2], covers a range of classified component parts on the basis of ISO fire conditions and generally verifies that the required fire resistance time of each particular structural element (e.g. walls, columns, ceilings) is complied with.

The following method leads to a fire safety concept which covers the respective single case only up to a limited extent. Recent performance based research work therefore aims to develop more realistic methods of fire engineering. In this context the „Natural Fire Safety Concept“ research project can be cited which is currently carried out by a European Commission promoted European research group. This paper is part of the aforementioned research project.

The specification of safety factors is of great importance for the structural design and, moreover, for fire safety engineering. After a short introduction to the basic principles of the reliability theory its application to fire safety engineering will be described in more detail.

2 Principle of Verification

For building structures in general, it must be verified that the stress values S_d do not exceed the resistance values R_d

$$S_d \leq R_d \qquad \text{Index d indicates the design values.} \qquad (1)$$

In structural design the stresses or forces caused by loading are defined as stress values S_d (S for stress) and the limit stresses or limit section forces as resistance values R_d (R for resistance). The design values S_d and R_d are generally determined on the basis of partial safety factors from characteristic values (Index k). Assuming linear relations between actions and section forces the following design values S_d and R_d are obtained:

$$S_d = \gamma_S \cdot S_K \qquad (2)$$

$$R_d = R_k / \gamma_R \qquad (3)$$

Thus we obtain for condition (1)

$$\gamma_S \cdot S_k \leq R_k / \gamma_R \qquad (4)$$

or

$$\gamma \cdot S_k \leq R_k \qquad (5)$$

assuming that $\gamma_S \cdot \gamma_R = \gamma$. Here γ is the global safety factor.

The quantities S and R are random variables as seen statistically. The spread of the relative values s and r is taken into account by distribution functions. Generally used distribution functions in structural design are [9]:

- the normal distribution (e.g. for permanent loads and material properties)
- the lognormal distribution (e.g. for strength properties, fatigue design and accidental action like fire load)
- extreme value distribution: Gumbel or Weibull distribution (e.g. for random action).

The normal and lognormal distributions will be described in the following section in more detail. They are the basis for the determination of safety factors and characteristic values.

The partial safety factors γ_S and γ_R guarantee a certain safety level. The spread of the values S and R is relevant for the determination of γ_S and γ_R. Additional factors, which are taken into account for γ_S and γ_R are important to cover uncertainties in the mechanical and stochastic model, and to consider particular sensitivities of the system (see also [8], [9]).

3 Distribution functions for continuous random variables

3.1 Principles

For steady random variables (here: random variable S with values x) the distribution function is generally defined as follows [14]:

$$F(x_p) = \int_{-\infty}^{x_p} f(x) \cdot dx \tag{6}$$

The function f(x) stands for the density of the distribution.
Due to lim $F(x_p) = 1$ for $x_p \rightarrow \infty$ the following applies:

$$\int_{-\infty}^{+\infty} f(x) \cdot dx = 1 \tag{7}$$

3.2 Normal distribution

For normal distribution (Gaussian distribution) of the random variable X the function of the distribution density is the well-known Gaussian bell-shaped curve:

$$f(x) = \frac{1}{\sigma_x \cdot \sqrt{2\pi}} \cdot e^{-\frac{1}{2}\left(\frac{x - m_x}{\sigma_x}\right)^2} \tag{8}$$

The maximum of the curve reaches $x = m_x$. It is symmetrical to the mean value m_x and contains two turning points which have a distance of $\pm\sigma_x$ (standard deviation) to the mean value, see Figure A1. The equations (6) and (8) provide the distribution functions of the normal distribution for:

$$F(x_p) = \frac{1}{\sigma_x \cdot \sqrt{2\pi}} \cdot \int_{-\infty}^{x_p} e^{-\frac{1}{2}\left(\frac{x - m_x}{\sigma_x}\right)^2} \cdot dx \tag{9}$$

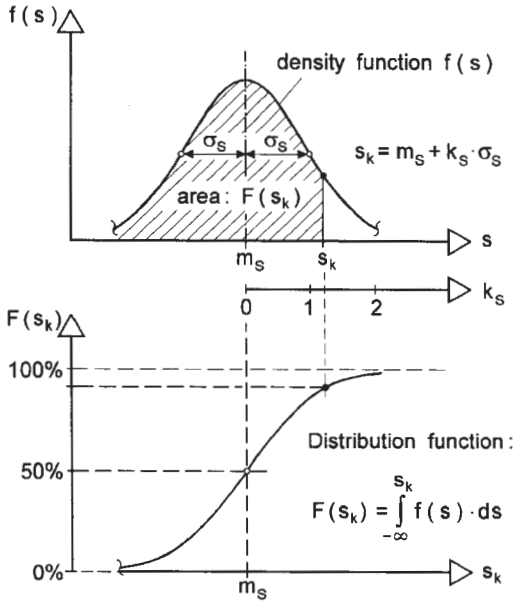


Figure A1: Distribution function F (x_p) (bottom) and density function f (x) (top) of the normal distribution

The variation coefficient

$$V_x = \frac{\sigma_x}{m_x} \tag{10}$$

is another parameter of the normal distribution.
If the exponent of equation (8) is defined as a reference variable δ

$$\delta = \frac{x - m_x}{\sigma_x} \tag{11}$$

x values are obtained for the given values m_x and σ_x as a function of δ

$$x = m_x + \delta \cdot \sigma_x = m_x \cdot (1 + \delta \cdot V_x) \tag{12}$$

For the integration limit x_p of the distribution function F (x_p) we obtain analogous to equation (12)

$$x_p = m_x + \delta_p \cdot \sigma_x = m_x \cdot (1 + \delta_p \cdot V_x) \tag{13}$$

The probability p (δ_p) for the occurrence of $x \leq x_p$ corresponds to the relevant value F (x_p) and F (δ_p) respectively of the distribution function. Table A1 shows a number of value pairs. The fractile values k_R and k_S will be required later.

p (δ_p)	δ_p	k_R and k_S
2,50 %	- 1,960	
5,00 %	- 1,645	
10,00 %	- 1,282	$k_R = - \delta_p$
15,87 %	- 1,000	
20,00 %	- 0,842	
50,00 %	0	
80,00 %	+ 0,842	
84,13 %	+ 1,000	
90,00 %	+ 1,282	$k_S = + \delta_p$
95,00 %	+ 1,645	
97,50 %	+ 1,960	

Table A1: Occurrence probability p (δ_p) for $x \leq x_p$ and fractile values k_R, k_S

3.3 Lognormal distribution

The lognormal distribution presumes that the natural logarithms $\overline{X}$ of the random variable X ($\overline{X} = In\,X$) are normally distributed, meaning that

$\overline{x} = In\,x$ applies to the values.

The mean value is described as $\overline{m}_x$ and the standard deviation as $\overline{\sigma}_x$.

$$\frac{d\overline{x}}{dx} = \frac{1}{x} \tag{15}$$

The distribution function and the density function can be expressed, dependent on x_p and x respectively, using equation (15) as:

$$F(x_p) = \frac{1}{\bar{\sigma}_x \cdot \sqrt{2\pi}} \cdot \int_{-\infty}^{x_p} e^{-\frac{1}{2}\left(\frac{\ln x - \bar{m}_x}{\bar{\sigma}_x}\right)^2} \cdot \frac{1}{x} \cdot dx \tag{16}$$

$$f(x) = \frac{1}{x \cdot \bar{\sigma}_x \cdot \sqrt{2\pi}} \cdot e^{-\frac{1}{2}\left(\frac{\ln x - \bar{m}_x}{\bar{\sigma}_x}\right)^2} \tag{17}$$

Equations (16) and (17) only apply to positive x-values. For $x \leq 0$ it becomes $f(x) = 0$ and $F(x_p) = 0$, [14].

Figure A2 shows an example of the distribution density function f (x).

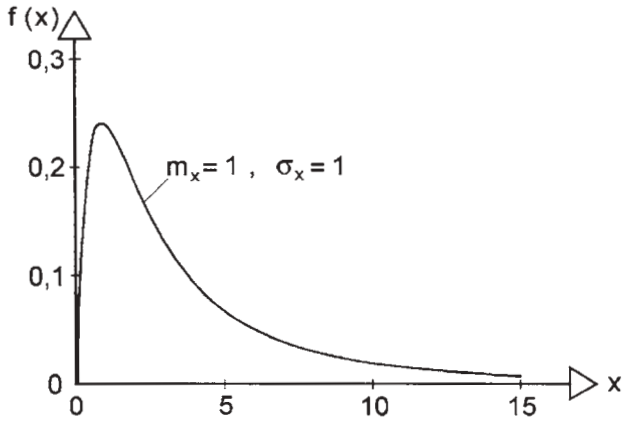


Figure A2: Density function f (x) of the lognormal distribution (example).

Analogous to the normal distribution we obtain for the lognormal distribution:

$$\delta = \frac{\ln x - \bar{m}_x}{\bar{\sigma}_x} \tag{18}$$

$$\bar{x}_p = \ln x_p = \bar{m}_x + \delta_p \cdot \bar{\sigma}_x \tag{19}$$

$$x_p = e^{\bar{m}_x + \delta_p \cdot \bar{\sigma}_x} \tag{20}$$

The correlation's between the characteristics of the normal distribution and the lognormal distribution are required for further calculations.

$$m_x = e^{\bar{m}_x + \frac{1}{2}\bar{\sigma}_x^2} \tag{21}$$

$$\sigma_x^2 = m_x^2 \cdot \left(e^{\bar{\sigma}_x^2} - 1 \right) \tag{22}$$

$$V_x^2 = e^{\bar{\sigma}_x^2} - 1 \tag{23}$$

$$\bar{m}_x = \ln m_x - \frac{1}{2} \cdot \ln\left(1 + V_x^2\right) \tag{24}$$

$$\bar{\sigma}_x = \sqrt{\ln\left(1 + V_x^2\right)} \tag{25}$$

as well as with equations (20) and (21)

$$x_p = m_x \cdot e^{\delta_p \cdot \bar{\sigma}_x - \frac{1}{2}\bar{\sigma}_x^2} \tag{26}$$

An evaluation of equation (25) in Table A2 shows that for $V_x \leq 0{,}3$

$$\bar{\sigma}_x = V_x \tag{27}$$

can be used as an approximation. For equation (26) the following approximation applies:

$$x_p = m_x \cdot e^{\delta_p \cdot V_x - \frac{1}{2} \cdot V_x^2} \tag{28}$$

V_x	$\bar{\sigma}_x = \sqrt{\ln\left(1+V_x^2\right)}$
0,00	0,000
0,05	0,050
0,10	0,100
0,15	0,149
0,20	0,198
0,25	0,246
0,30	0,294
0,35	0,340
0,40	0,385
0,45	0,429
0,50	0,472
0,55	0,514
0,60	0,555
0,65	0,594
0,70	0,632

Table A2: Standard deviation $\bar{\sigma}_x$ of the lognormal distribution for different variation coefficients V_x

4 Normal distribution of S and R

Under the assumption of a normal distribution of the random values S and R, the distribution functions and the density function can be determined by means of equations (8) and (9). The principal correlation's for the verification $s_d \leq r_d$ are shown in Figure A3:

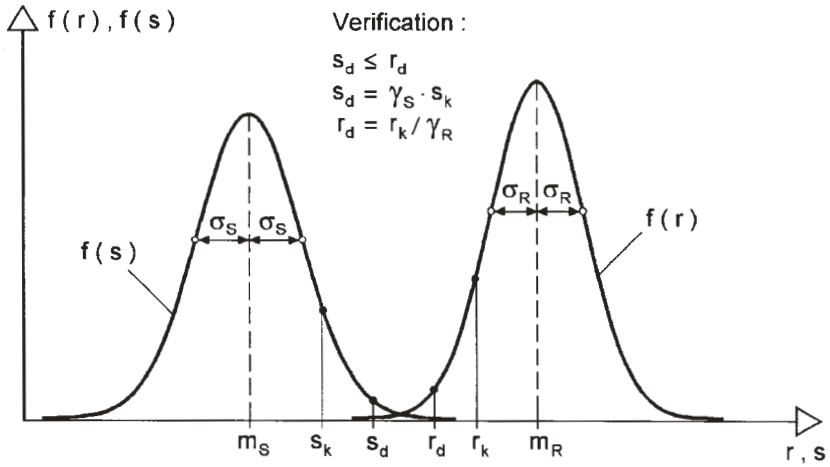


Figure A3: Verification $s_d \leq r_d$ for normally distributed random variables S and R

The characteristic values and the design values form the basis of the verification concept (see section 2 resp. Figure A3). With reference to equation (12) they can be formulated as follows:

$$s_k = m_S + k_S \cdot \sigma_S = m_S \cdot (1 + k_S \cdot V_S) \quad (29)$$

$$r_k = m_R - k_R \cdot \sigma_R = m_R \cdot (1 - k_R \cdot V_R) \quad (30)$$

$$s_d = m_S + \alpha_S \cdot \beta \cdot \sigma_S = m_S \cdot (1 + \alpha_S \cdot \beta \cdot V_S) \quad (31)$$

$$r_d = m_R - \alpha_R \cdot \beta \cdot \sigma_R = m_R \cdot (1 - \alpha_R \cdot \beta \cdot V_R) \quad (32)$$

k_S and k_R are so-called fractile values to determine the characteristic values s_K and r_K. They may be taken from Table A1. If, e.g., the fractile value 90 % is taken for the random value S and the 10 % fractile value for the random value R, the result is k_S and k_R = 1,282.

Before considering the parameters α_S, α_R *and* β (weighting factors and safety indices) in more details the formulas for the partial safety factors γ_S *and* γ_R must be determined. By using the equations (2), (3) and (29) to (32) we get:

$$\gamma_S = \frac{s_d}{s_k} = \frac{1 + \alpha_S \cdot \beta \cdot V_S}{1 + k_S \cdot V_S} \quad (33)$$

$$\gamma_R = \frac{r_k}{r_d} = \frac{1 - k_R \cdot V_R}{1 - \alpha_R \cdot \beta \cdot V_R} \tag{34}$$

Since the random variables R and S are normally distributed, the difference Z = R - S is also normally distributed. Mean value and standard deviation of Z are then

$$m_Z = m_R - m_S \tag{35}$$

$$\sigma_Z = \sqrt{\sigma_R^2 + \sigma_S^2} \tag{36}$$

The values of the random variable Z are calculated according to z = r - s. Then the following design value applies:

$$z_d = r_d - s_d \tag{37}$$

The requirement that the stress values may not exceed the resistance values results in the following limit condition:

$$z_d = r_d - s_d = 0 \tag{38}$$

Due to the normal distribution of the random variable Z, the design value z_d can also be described as follows according to Figure A4:

$$z_d = m_z - \beta \cdot \sigma_z = 0 \tag{39}$$

In structural design the occurrence of $z \leq z_d$ is tolerated with a given probability which is called „failure probability“ p_f (f: failure) and depends on the safety index β, see also [13]. The notation of equation (39) corresponds to the definition of a lower fractile value.

Table A1 generally shows the correlation between p_f and β, ($(p_f = p(\delta_p)$ and $\beta = -\delta_p$). The safety index can be determined on the basis of the failure probability by using the distribution function Φ of the standard normal distribution:

$$p_f = \Phi(-\beta) \tag{40}.$$

The numerical values of the distribution function Φ are listed in the references ([15][16]).

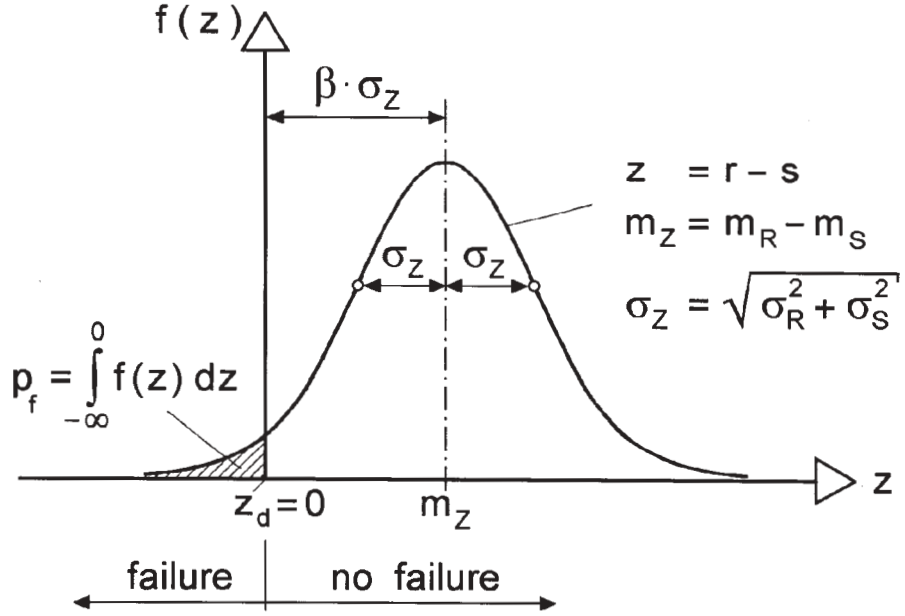
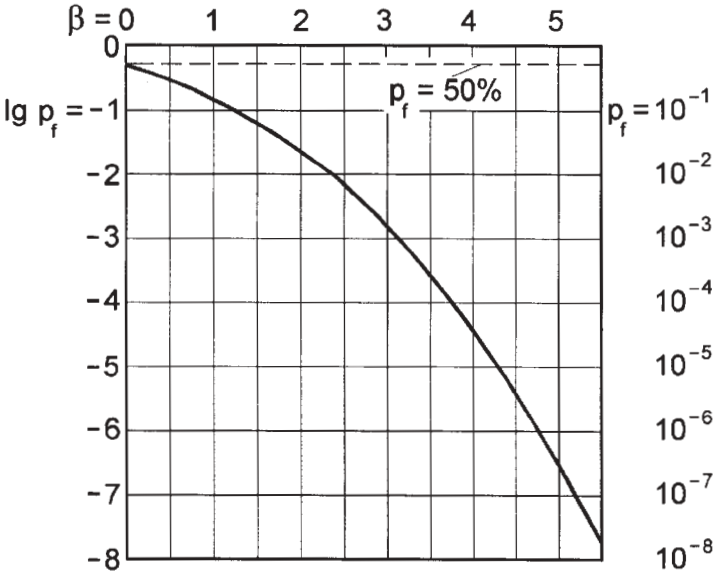


Figure A4: Density function f(z), failure probability p_f and safety index β



p_f	β
50% = 0,5	0,000
20,0%	0,842
15,9%	1,000
10,0%	1,282
5,0%	1,645
2,5%	1,960
$2{,}28 \cdot 10^{-2}$	2,000
$1{,}00 \cdot 10^{-2}$	2,326
$1{,}35 \cdot 10^{-3}$	3,000
$1{,}00 \cdot 10^{-3}$	3,090
$1{,}00 \cdot 10^{-4}$	3,719
$3{,}17 \cdot 10^{-5}$	4,000
$1{,}00 \cdot 10^{-5}$	4,265
$1{,}00 \cdot 10^{-6}$	4,753
$2{,}87 \cdot 10^{-7}$	5,000
$1{,}00 \cdot 10^{-7}$	5,200
$1{,}00 \cdot 10^{-8}$	5,612

Figure A5: Failure probability p_f and safety index β

From equations (38), (39), (31) and (32) the following condition can be derived for the weighting factors:

$$\alpha_S \cdot \sigma_S + \alpha_R \cdot \sigma_R = \sigma_Z \tag{41}$$

The weighting factors are defined as

$$\alpha_S = \sigma_S / \sigma_Z \text{ and } \alpha_R = \sigma_R / \sigma_Z \tag{42}$$

This leads to the following transformation of equation (41):

$$\alpha_S^2 + \alpha_R^2 = 1 \tag{43}$$

Figure A6 shows the weighting factors according to equations (42) and (36) in relation to the ratio σ_S/σ_R. In the relevant literature the weighting factor α_S is generally written with a minus sign. This is the consequence when the plus sign is replaced by a minus in equation (31). In many cases the weighting factors have to cover a wide distribution range of the random variables S and R. In many applications such numerical values are chosen which, used in equation (43), result in values greater than 1. Eurocode 1 [7], for instance, has fixed the values α_S = - 0,7 and α_R = 0,8.

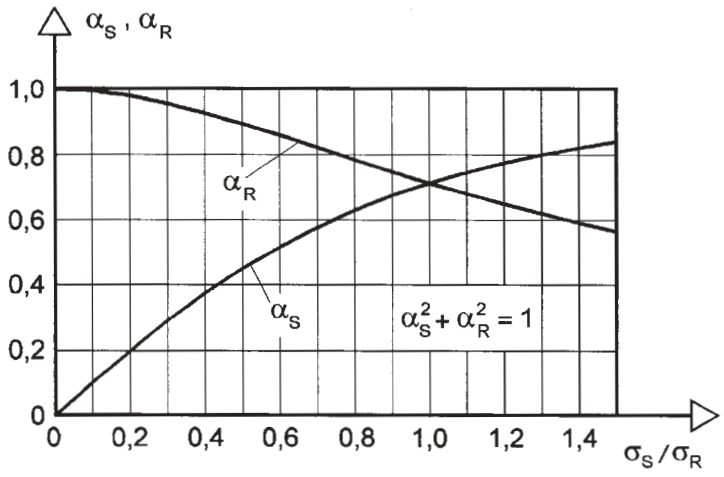


Figure A6: Weighting factors α_S and α_R

5 Lognormal Distribution of S and R

Now it is presumed that the natural logarithms of the random values S and R are normally distributed. Those values which refer to the natural logarithms are marked with a bar, as shown in section 3.3. Here are $ln\, s = \bar{s}$ *and* $ln\, r = \bar{r}$.
Analogous to the notation of the equations (29) and (32) the characteristic and design values can be described by equations (19) and (20):

$$\bar{s}_k = \ln s_k = \bar{m}_S + k_S \cdot \bar{\sigma}_S \quad \Rightarrow s_k = e^{\bar{m}_S + k_S \cdot \bar{\sigma}_S} \tag{44}$$

$$\bar{r}_k = \ln r_k = \bar{m}_R - k_R \cdot \bar{\sigma}_R \quad \Rightarrow r_k = e^{\bar{m}_R - k_R \cdot \bar{\sigma}_R} \tag{45}$$

$$\bar{s}_d = \ln s_d = \bar{m}_S + \alpha_S \cdot \beta \cdot \bar{\sigma}_S \Rightarrow s_d = e^{\bar{m}_S + \alpha_S \cdot \beta \cdot \bar{\sigma}_S} \tag{46}$$

$$\bar{r}_d = \ln r_d = \bar{m}_R - \alpha_R \cdot \beta \cdot \bar{\sigma}_R \Rightarrow r_d = e^{\bar{m}_R - \alpha_R \cdot \beta \cdot \bar{\sigma}_R} \tag{47}$$

For the partial safety factors we get

$$\gamma_S = \frac{s_d}{s_k} = e^{\alpha_S \cdot \beta \cdot \bar{\sigma}_S - k_S \cdot \bar{\sigma}_S} \tag{48}$$

$$\gamma_R = \frac{r_k}{r_d} = e^{\alpha_R \cdot \beta \cdot \bar{\sigma}_R - k_R \cdot \bar{\sigma}_R} \tag{49}$$

The natural logarithms of the limit condition $s_d/r_d = 1$ give

$$\ln r_d - \ln s_d = 0 \tag{50}$$

Analogous to equation (39)

$$\bar{m}_Z - \beta \cdot \bar{\sigma}_Z = 0 \tag{51}$$

is now required. Presuming the lognormal distribution of S and R

$$\bar{m}_Z = \bar{m}_R - \bar{m}_S \tag{52}$$

and

$$\bar{\sigma}_Z = \sqrt{\bar{\sigma}_R^2 + \bar{\sigma}_S^2} \text{ apply.} \tag{53}$$

Similar to equation (41) we obtain for the weighting factors:

$$\alpha_R \cdot \bar{\sigma}_R + \alpha_S \cdot \bar{\sigma}_S = \bar{\sigma}_Z \tag{54}$$

The global safety factor γ results in

$$\gamma = \gamma_S \cdot \gamma_R = \frac{s_d \cdot r_k}{s_k \cdot r_d} = e^{\beta \cdot \bar{\sigma}_Z - k_R \cdot \bar{\sigma}_R - k_S \cdot \bar{\sigma}_S} \tag{55}$$

The standard deviations can be formulated by the variation coefficients $V_R = \sigma_R/m_R$ and $V_S = \sigma_S/m_S$ according to equation (25).

$$\bar{\sigma}_S = \sqrt{\ln\left(1+V_S^2\right)} \tag{56}$$

$$\bar{\sigma}_R = \sqrt{\ln\left(1+V_R^2\right)} \tag{57}$$

$\bar{\sigma}_S = V_S$ und $\bar{\sigma}_R = V_R$ can be set with a good approximation for small numerical values of the variation coefficients V_S and $V_R \leq 0{,}3$ (see Table A2). This leads to the following approximate equation for the safety factor γ :

$$\gamma = e^{\beta \cdot \sqrt{V_R^2 + V_S^2} - k_R \cdot V_R - k_S \cdot V_S} \tag{58}$$

For given failure probabilities p_f the safety index β can be determined on the basis of Figure A5, the fractile factors k_R and k_S by means of Table A1.

6 Fire Safety Engineering for Industrial Buildings

6.1 Design concept

DIN V 18230 (Sept./1987) and E DIN 18230 (March/1996) contain requirements for the fire engineering of buildings or building parts which are intended for production or storage purposes within a company (industrial buildings).
The principal design concept will be roughly described in the following with reference to E DIN 18230 [5].

The equivalent fire duration time $t_{ä}$ is the basis for the determination of the calculated fire resistance time erf t_F

$$t_{ä} = q_R \cdot c \cdot w \qquad (59)$$

Here are q_R design fire load in kWh/m^2
c conversion factor in min ·m^2/kWh
w ventilation factor

The time equivalent $t_{ä}$ indicates the fire span in minutes in which the reference component part approximatively suffers the same fire impact under ISO-fire conditions (ETK, see DIN 4102 Part 2, [1]) as under natural fire conditions. The required fire resistance time t_F is calculated as follows:

$$\text{erf } t_F = t_{ä} \cdot \gamma \cdot \alpha_L .$$

Here are

γ safety factor for structural elements of the fire safety class SK_b3 with high requirements (for component parts within the fire safety classes SK_b 2 and SK_b1 with lower safety requirements, the factor δ must be used instead of γ).

α_L additional factor to consider fire containment due to the technical fire safety infrastructure.

The definition of the factors γ and α_L will be described in the next section in more detail. On the basis of the calculated fire resistance time erf t_F according to equation (60) the component parts can be related to the corresponding fire resistance classes of DIN 4102 Part 2, see Table A3.

erf t_F	Fire resistance class
0 < erf $t_F \leq$ 15 min	none
15 < " $\leq$ 30 min	F 30
30 < " $\leq$ 60 min	F 60
60 < " $\leq$ 90 min	F 90
90 < " $\leq$ 120 min	F 120

Table A3: Classification of the fire resistance classes in relation to erf t_F.

The values defining the fire resistance classes stand for the minimum fire resistance time in minutes under ISO-conditions. The verification of the fire resistance classes according to DIN 4102 Part 2 may be determined with or without fire tests.

a) With fire tests
The fire resistance class of the component parts must be verified by means of a certification based on tests according to DIN 4102 Part 2.

b) Without fire tests
The component parts which are listed up in DIN 4102 Part 4 are related tofire resistance classes and do not require any further verification.

In addition to that the requirements of the Industriebaurichtlinie [3] must be complied with.

6.2 Safety Factors

The design concept according to section 6.1 compares the equivalent fire duration time $t_{ä}$ with the fire resistance time F of the component part, whilst maintaining a sufficient safety distance $\gamma \cdot \alpha_L$. Logarithmic normal distributions according to [18] apply to the distribution functions $t_{ä}$ and F. Then the safety factor γ can be determined by equation (55):

$$\gamma = e^{\beta \cdot \bar{\sigma}_Z - k_R \cdot \bar{\sigma}_R - k_S \cdot \bar{\sigma}_S}$$

The logarithmic standard deviations $\bar{\sigma}_S$ und $\bar{\sigma}_R$ can be calculated by means of equations (56) and (57) for the prescribed variation coefficients V_S and V_R . $\bar{\sigma}_z$ derives from equation (53). In the following the generally applicable descriptions are also used as in chapter 5. The index „S“ corresponds in fire engineering to the fire impact ($t_{ä}$ according to the DIN 18230 concept) and index „R“ to the existing fire resistance time „F“.

In order to obtain the safety factor γ in accordance with equ. (55) the safety index β must be known. It is the corresponding value to the target failure probability p_{fb} due to fire impact. With reference to the detailed derivations in [18], p_{fb} can be determined as follows:

$$p_{fb} = \frac{\lim p_{fi}}{p_1 \cdot p_2 \cdot p_3 \cdot A} \tag{61}$$

here are

lim p_{fi}: target failure probability per year [1/p.a.] in the case of fire; Index „i" stands for the fire safety classes SK_b3, SK_b2 and SK_b1

p_1: mean occurrence probability of fires per m^2 in a fire compartment per year

p_2: design factor for the fire fighting measures (public fire brigade, works fire brigade)

p_3: design factor for the consideration of suitable fire fighting devices

A: floor area of the fire compartment in m^2.

Table A4 provides a summary of the parameters required for equations (61) and (55) according to [18], [4] and [5]. With p_{fb} the safety index β can be determined by means of equ. (61) and Figure A5 and can be used for equation (55) finally.

The fractile values k_S and k_R are valid for the 90 % fractile of the equivalent fire duration time and the 10 % fractile of the fire resistance time and can also be taken from Table A1. The variation coefficient V_R = 0,2 resp. 0,25 applies to the fire resistance time determined by fire tests. They must be interpreted as an approximation, see [18]. The factors - lim p_{f3} - are applicable to the fire safety classes SK_b3. For SK_b2 the values have to be multiplied by 10 and for SK_b1 by 100, see also [4], [5] and [18].

[18] considers the influence of the area of the fire compartment A on the fire fighting possibilities by the additional factor A*/A in equation (61), where A* = 2500 m^2. Evaluations of equation (55) with parameters from Table A4 and equ. (61) reveal that this additional factor apparently has also been used in [4] for multi-storey buildings. The safety factors according to equation (55) are slightly greater than the values shown in [5]. The possible use of other additional factors in [5] is not obvious.

Source	lim p_{f3} [1/p.a.] single-storey	lim p_{f3} [1/p.a.] multi-storey	p_1 [1/(m^2·p.a.)]	p_2 [-]	V_S [-]	V_R [-]	k_S and k_R [-]
Bub, [18]	2.10^{-6}	10^{-6}	2.10^{-6}	0,1	0,25	0,2	1,282
DIN V 18230 (1987), [4]	10^{-5}	10^{-6}	2.10^{-6}	0,1	0,25	0,2	1,282
E DIN 18230 (1996), [5]	5.10^{-6}	10^{-5}	10^{-5}	0,1	0,25	0,25	1,282

Table A4: Statistical parameters for the determination of the safety factor γ according to [18], [4] and [5]

The limit values of the target failure probability lim p_f are based on the number of involved people at risk. For buildings the accepted probability of accidents with fatalities is about 10^{-6} per year and endangered person, [13]. The number of people at risk which might be expected therefore determines the factor lim p_f. Eurocode 1 [7] defines the limit values for the safety index β according to Table A5 for the assessment of the load bearing capacity and the serviceability. However, the number of persons endangered by the failure of different component parts has not been taken into account. The values of the target failure probability lim p_f according to Table A5 which belong to lim β may be used to evaluate the target failure probabilities in Table A4. The parameters in Table A5 are based on a building lifetime of approx. 50 years.

Limit condition	lim β		lim p_f	
	1 year	life span	1 year	life span
Load bearing capacity	4,7	3,8	$1{,}3 \cdot 10^{-6}$	$7{,}2 \cdot 10^{-5}$
Serviceability	3,0	1,5	$1{,}3 \cdot 10^{-3}$	$6{,}7 \cdot 10^{-2}$

Table A5: Limit values for the safety index β according to Eurocode 1 and failure probability p_f

The design concept of [5] determines the safety factor γ for equation (60) by means of equation (55) and $p_2 = 0{,}1$ as well as $p_3 = 1$ in equation (61). Hereby the possibility that the fire ignition developed to a flashover fire is taken into account with $p_2 = 0{,}1$ for the public fire brigade. The additional factor in equation (60) is then $\alpha_L = 1$. A possible fire safety infrastructure can be assessed on the basis of the additional factors $\alpha_L < 1$. Table A6 shows some values for α_L based on Table A6 in [5]:

Fire safety infrastructure	α_L	$p_2 \cdot p_3 / 0{,}1$
sprinkler system	0,6	0,01
automatic fire detection	0,9	0,5
full-time work fire brigade		
with 6 persons per shift	0,9	0,5
with 12 persons per shift	0,8	0,1
with 18 persons per shift	0,7	0,05
with 24 persons per shift	0,6	0,01

Table A6: Additional safety factor α_L according to DIN 18230 [5] and corresponding failure probabilities

The additional factors α_L are obtained approximately for the failure probabilities shown in Table A6, see also [18]. On the basis of equations (55) and (60) it is

$$\alpha_L = e^{(\beta_L - \beta) \cdot \bar{\sigma}_Z} \tag{62}$$

with

β_L according to equ. (61) for $p_2 \cdot p_3 = 0{,}1$ (public fire brigade only)

β_L according to equ. (61) for $p_2 \cdot p_3$ (with additional measures as shown in Table A6)

α_L according to equation (62) depends on β_L and β. If the target failure probabilities of Table A6 are assumed to be realistic, the values α_L according to Table A6 resp. [5] are approximations, which, however, considerably simplify the verification concept. The chosen procedure makes it possible to take further fire detection and fire fighting measures by the additional factor α_L into account, as far as reliable statistics of the corresponding target failure probabilities are available. The Swiss documentation SIA 81 [8] contains, for instance, additional measures which exceed the regulations of DIN 18230.

7 Fire safety design for other types of buildings

The approach for the fire safety design for industrial buildings as described in chapter 6 may also be used for other types of buildings. Fundamental preconditions are, however, that the prevailing fire load and the statistical parameters (analogous to Table A4) can be determined exactly.

Table A7 shows a summary of statistical parameters for other types of buildings. Here the limit values for the target failure probabilities lim p_f have been taken from [22], resp. [23]. The fire occurrence probability p_1 as well as the variation coefficients V_S correspond to [18], [19], [22] and [24]. The relevant safety factors γ then can be determined by means of equation (55) based on equation (61).

Table A8 shows a summary of a numerical investigation on the basis of the factors of Table A7. Here the first value is the respective safety factor γ for a fire compartment of 2500 m^2. The second value refers to an area of A = 10.000 m^2. For the intermediary areas the safety factors lie between these values.

Type of building	lim p_f [1/p.a.] single-storey	multi-storey	p_1 [1/(m²·p.a.)]	p_2 [-]	V_S [-]	V_R [-]	k_S, k_R [-]
-							
residential	$2 \cdot 10^{-6}$	$2 \cdot 10^{-8}$	$2 \cdot 10^{-7}$	0,1	0,4	0,25	1,282
buildings	$2 \cdot 10^{-6}$	$2 \cdot 10^{-7}$	10^{-6}	0,1	0,3	0,25	1,282
-shops							
-office	$2 \cdot 10^{-6}$	$2 \cdot 10^{-7}$	$5 \cdot 10^{-7}$	0,1	0,45	0,25	1,282
buildings	$2 \cdot 10^{-6}$	$2 \cdot 10^{-7}$	$5 \cdot 10^{-7}$	0,1	0,35	0,25	1,282
-schools	$2 \cdot 10^{-8}$	$2 \cdot 10^{-9}$	$5 \cdot 10^{-7}$	0,1	0,35	0,25	1,282
-hotels, hospitals							

Table A7: Statistical parameters for different types of buildings

Type of building	single-storey	multi-storey
Industrial buildings (Parameters acc. [5])	1,08 ... 1,30	1,34 ... 1,56
residential buildings	0,99 ... 1,29	2,06 ... 2,44
shops	1,26 ... 1,51	1,68 ... 1,94
office buildings	1,22 ... 1,56	1,81 ... 2,21
schools	1,16 ... 1,44	1,63 ... 1,93
hotels, hospitals	2,14 ... 2,47	2,71 ... 3,08

Table A8: Safety factor γ for the structural fire protection of buildings for A = 2500 m² and (...) A = 10.000 m²

The additional safety factors of Table A8 allow for the comparison of different types of buildings as well as a general appraisal. They take specific safety requirements and influences with regard to fire ignition conditions into consideration. Due to the consequently used safety concept a comparable safety level is obtained for different types of buildings.

8 Additional Remarks

The prescribed procedure of structural fire engineering offers the possibility to provide a fire safety concept for a certain building considering the respective boundary conditions as well as the intended active fire measures. The understanding of the theory of reliability may be helpful in certain cases to develop special solutions for the realization of the fire safety requirements. It is possible to extend the approach by further measures to improve the fire safety concept and to adapt the statistical basic parameters to new evaluation results of updated fire statistics.

The probabilistic approach is generally accepted and can be applied to other design forms within the field of fire safety engineering. The orientation towards DIN 18230 and the equivalent fire duration concept is not compulsory.

Analogous to Eurocode 1 Part 2-2 [10] it may be possible to use the additional safety factors to calculate a design value of the fire load q_d:

$$q_d = \gamma \cdot \alpha_L \cdot q_R \tag{63}$$

This would allow to show that the fire load is independent of the time equivalent and later on to replace the ISO-curve by a more realistical natural fire curve. With regard to the resistance side the corresponding limit values for the fire load would have to be determined afterwards [26], [27].

As an alternative, the procedure could be integrated into a hot design concept similar to Eurocode 3, Part 1-2 [11]. The stress can be described as a thermal development in the component parts. Heating curves for fire action are already included in Eurocode 1 Part 2-2 [10].

The temperature-dependent material properties can be used as resistance values. Then fire safety engineering can be conducted in form of a safety design which combines, as in Eurocode 1 [7], the fire stress value as an exceptional load case in a load combination with the permanent and variable loads.

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ANNEX B

1 GENERAL

1.1 How safe is safe enough?

Whatever measurers are taken to reduce the consequences of fire, people may still be killed in a building fire. We must accept that there is no absolute safety. It is therefore important to establish criteria to answer the key question: 'how safe is safe enough?'. For fire safety engineering the definition of acceptance criteria against which the adequacy of a design can be judged is an important first step in design.

1.2 Types of criteria

The following types of criteria are typically used:

a. Prescriptive (following prescriptions given by codes is deemed to satisfy)
b. Deterministic (scenario-based, when appropriate using safety factors)
c. Probabilistic (risk-based)
d. Comparative (comparison of performance with accepted codes of practice)
e. Systems approach

While for the fire design of an individual member a probabilistic approach is feasible the design process of a whole building is a complex procedure which normally requires a combination of the above criteria (see chapter 6) for analysing different scenarios and evaluating the safety reached by different measures.

1.3 Some characteristics of the above design approaches

The *prescriptive approach* is easiest to be applied by the designer and judged by the authority. However it's application does not lead to a coherent safety level and it may be over conservative and costly or unsafe. The objectives persued by the prescriptive measures are often not clear.

The *deterministic approach* depends on the consensus on the 'worst credible scenarios' to be established between the designer and the authority. Codes of practice defining characteristic input data and safety factors are common in structural engineering, but not yet much developed for fire design.

In EC 1-2.2 [1] fire is considered as an accidental action. The background document to EC 1-1 [2] and [15] gives as a benchmark for an accidental action as an action having a frequency of occurrence of 10^{-4} per year. The probability of a severe fire occurrence is approximately $0,3 \div 1,5 \cdot 10^{-6}/m^2 \cdot$ year (see 2.7.4.2). The consideration of fire as an accidental action is therefore justified.

The *probabilistic approach* is technically the most straightforward. However the definition of a probabilistic acceptance criteria (e.g. probability of death per year for an individual member of the public), is a very sensitive topic and difficult to communicate (an improvement in communication can be found by defining the probability of not being killed in a building fire e.g. 99,9990% per year, instead of the probability of death e.g. 10^{-5} per year).

The *comparative approach* is usually the easiest way to communicate an acceptable safety level because the solutions defined in prescriptive codes are considered as acceptable and can be used as a benchmark. Safety factors are normally not needed as inaccuracies have less effect on the result than in a full deterministic or probabilistic approach (because they level them self largely out). The disadvantage of the comparative approach is that the level of safety is not clearly defined in prescriptive codes and may differ from case to case.

1.4 Level of safety

The appropriate level of safety has to be based on a social consensus. Experience suggests that the public broadly tolerates the present average risk of death from fire. However statistics show that the number of fire death differ from country to country (e.g. the individual risk of fire death in western countries is between 0,5 to $2{,}5 \cdot 10^{-5}$ (fatalities per year / inhabitants) [3]). The acceptance of risk by the public is subjective and the range of acceptance is large and depends on several factors (number of casualties per incident, benefit and voluntariness etc.). To avoid this discussion, the safety level in present fire codes is implicitly given by prescribing detailed measures and not by general acceptance limits. However as absolute safety can not be reached, also prescriptive codes do accept an implicitly given risk of fire death.

1.5 Proposal for NFSC approach

An acceptance criterion is a very sensitive topic. To reach a general consensus on rational and explicit numbers to define the accepted risk will need much interdisciplinary discussion and communication (between regulators, politicians, physicists, scientists and public). NFSC will not be able to solve the problem of defining 'how safe is safe enough?', however it could contribute to the discussion.

However the development of ways to establish adequacy of a design is an important part of the NFSC work. For each design process the most appropriate type of criterion and approach (see 1.2) has to be chosen by the designer in a first step. (It is advisable to establish this first step in co-operation with the responsible checking authority). For individual members probabilistic or deterministic approaches are possible, for entire buildings, prescriptive, comparative or systems approaches should be considered.

Some guidance on how to choose the objectives and establish the design criteria is presented below.

2 PROBABILISTIC APPROACH

2.1 General

A rational approach to risk-based acceptance criteria ought to be to set a limit to the risk = probability · consequences, i. e.

$$R_{acc} = p \cdot C \tag{1}$$

p: frequency of occurrence (per period of time e.g. per year and per group or boundary considered e.g. 10^6 persons, country, building)
C: expected damage (e.g. number N of persons affected)

2.2 Individual risk to life

2.2.1 The individual risk to life – definition

The individual risk to life due to a specific hazard can be expressed as:

$$\text{individual risk} = \frac{\text{fatalities per year (for a given hazard)}}{\text{number of persons at risk (for a given hazard)}}$$

2.2.2 Individual risk to life for building fires

For fire the total amount of fatalities (CH ~ 30 fatalities/year) as well as the related individual risk ($0{,}4 \cdot 10^{-5}$ fatalities /inhabitant · year) is very low. This may reflect the present level of fire safety asked for in building regulations. Most fire death occurs at home therefore the individual risk at home is statistically larger than in public areas (statistic paper chapter 2.4.4 [17]).

2.2.3 Individual risk to life for other areas

Risk to life · 10^{-5} fatalities/(year·pers)	characterisation	Examples	· 10^{-5} fatalities/(year·pers)
> 1000	extremely high	climbing the Eiger North Wall	20.000
100 ... 1000	very high	accidental fall (age > 85 year)	700
30 ... 100	high	car driving (age 20 - 24 men)	33
		construction worker	65
10 ... 30	medium	car driving all	10
3 ... 10	low	machinery worker	4
0,3 ... 3	very low	pedestrian	3
		car driving (woman)	3
		fire (all reasons)	0,5
		fire (age 1 - 4)	0,6
		fire (age 65+)	0,7
		gardening	0,7
< 0,3	extremely low (neglectable)	lightning	0,05
		snake bite (Switzerland)	< 0,001

Table B1: Characterisation of the individual risk to life and some examples based on Swiss statistics [4]

The average life expectancy today in industrialised countries is around 75 years. The reasons for people dying and associated risk to life values are given in Table B2 (data from [4] for CH, G, UK, 5 years average).

When taking into account illness and accidents the term mortality rate is often used instead of individual risk to life. The definition is in principle the same. The number of persons at risk is normally the population of a given country or a sub group (e.g. smokers for lung cancer etc.)

One can see from tables B1 and B2 that health problems are responsible of approx. 95 % of all fatalities and that among violent death fire represents a very low individual risk.

Cause	Relative No of fatalities	Individual risk [$\cdot 10^{-5}$ fatalities/(year·pers)]
Illness total:	92 ÷ 96 %	842 ÷ 1130
- Cancer	23 ÷ 26 %	244 ÷ 270
- Circulatory failure	45 ÷ 50 %	414 ÷ 579
Violent death total:	4 ÷ 8 %	41 ÷ 77
- Accidents	2,5 ÷ 6 %	28 ÷ 52
- Suicide	0,75 ÷ 2,5 %	9 ÷ 23
- Murder	0,10 ÷ 0,35 %	1,2 ÷ 4,0

Table B2: Causes of human fatalities and individual risk to life (range of data for CH, G, UK, 5yr average [4] Table 3.1 and 3.3).

A comparison of tables B1 and B2 shows that the risk of fire death $0{,}50 \cdot 10^{-5}$ fatalities/(year·pers) is very low to other causes of human fatalities.

The individual risk to life is changing with age. Fig. 1 shows the risk to life as a function of age [4]. The smallest individual risk to life is found for girls aged 10 with $15 \cdot 10^{-5}$ and boys $30 \cdot 10^{-5}$ of the same age. (A comparison between Table B1 and Table B2 shows that the mortality rate is much higher than the risk to life for a specific hazard to which every body is exposed (e.g. fire) because the mortality rate is the sum of all risks including illness)

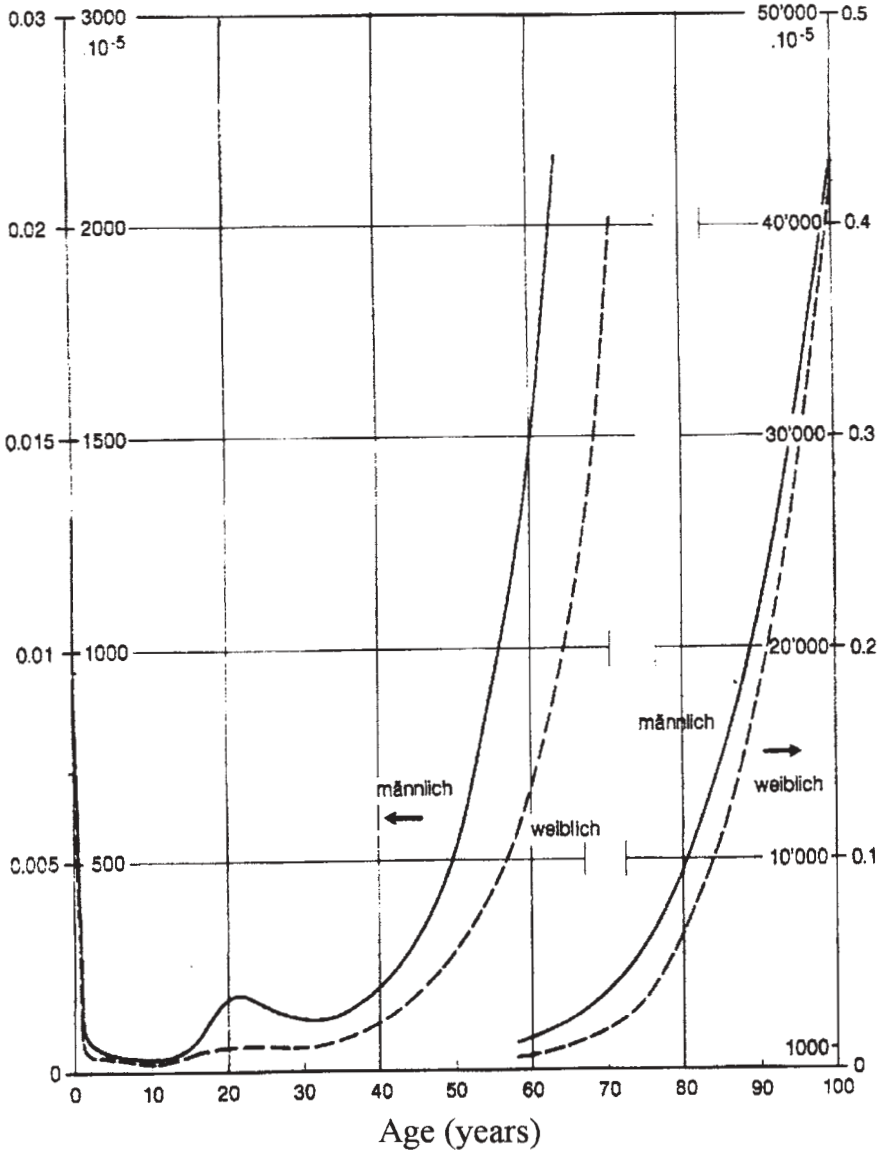

Figure B1: Individual risk to life (mortality rate) as a function of age, average 1978 to 1983 for Switzerland [4].

2.3 Subjective risk to life

The public tolerates the risk to life not objectively but in a subjective way, based on some aspects given below.

2.3.1 Benefit and control of activity

A general principle of risk acceptance is that the risk an individual is ready to take depends on to which extent he gets the benefit or is able to control the activity. Therefore, the acceptable risk at places of public assembly, hotels, etc. is lower than that in offices, industry or at home. For domestic premises, the accepted risk due to incidents in one's own home is higher than that due to incidents happening in one's neighbour.

2.3.2 Number of people involved

Multiple death – subjective risk perception
Experience suggests that people are less tolerant to accidents with high consequences (e.g. multiple fatalities N). Therefore, an acceptable level might be expressed in function of its consequences:

$$R_{acc,S} = p \cdot n \cdot N \qquad (2a)$$

or $$R_{acc,S} = p \cdot N^n, \quad \text{(where N > 1)} \qquad (2b)$$

p: frequency of occurrence (per year)
N: number N of persons affected (e.g. number of fatalities)

where $n \geq 1$. If $R_{acc,S}$ = constant is taken as the limit, a lower frequency is acceptable for accidents with higher consequences.

2.3.2.1 Societal risk to life

For society hazard evaluation is primarily based on the individual risk to life. Small risks to life may concern society if they lead to a substantial number of death e.g. the very high individual risk to life for civilian parachutists ($170 \cdot 10^{-5}$ fatalities / parachutists · yr) is accepted while the low to medium risks in road traffic ($10 \cdot 10^{-5}$ fatalities /inhabitant · yr) leading to a substantial number of fatalities each year (e.g. approx. 700 fatalities in CH only) are concerning the authorities.

2.4 Some acceptance criteria for fire found in literature

In comparing acceptance criteria from different sources it is important that the following factors are known:

- Is the data quoted per annum or otherwise (e.g. for the whole design life of a building; what time is taken as lifetime 50, 70 or 100 years?)
- To what "group" does it apply (e.g. to the whole of a country, or only to special group e.g. sports fans or to office-based employees)?
- The probability of what "event" is being parameterised (structural collapse, multiple fatalities etc)?

Example, consider a 10-fatality "event" as the outcome of a fire. The acceptance criteria for such an event may be assessed from experience in a given country with a common regulatory regime and a population of 50 million. That experience may show that over the last 10 years there has been 10 such events. This seems to be an acceptance criterion of 1 per annum.

However, the data may be a mixed population. Say 9 fires were in dwellings (which are more fire prone), and 1 was in a commercial building (e.g. a shop). This then indicates a societal risk of 10^{-1} pa for design of commercial buildings.

Perhaps a lower figure could be deduced for offices, but the data may not spread over a long enough period to find such an event. In addition, serious events often occur in older premises in which modern construction has not been used or in buildings where un-notified change of use or poor safety management has occurred.

To reduce the societal risk to an individual acceptance criterion one requires the relevant population on time period to be identified.

2.4.1 Data by Rasbash

Rasbash has discussed the problem of acceptance criteria for risk in fire in detail in Fire Safety Journal [5] and much of his data is based on the CIB design guide on structural fire safety [6]. Some data is given in Tables B3 and B4 and Figures B2 and B3.

Expected number of fatalities in case of fire	Economic losses					
	Low		Medium		Small	
	Lifetime	Annual[1]	Lifetime	Annual[1]	Lifetime	Annual[1]
Low (≈ 0,1)	10^{-3}	$2 \cdot 10^{-5}$	10^{-4}	$2 \cdot 10^{-6}$	10^{-5}	$2 \cdot 10^{-7}$
Medium (≈ 1,0)	10^{-4}	$2 \cdot 10^{-6}$	10^{-5}	$2 \cdot 10^{-7}$	10^{-6}	$2 \cdot 10^{-8}$
High (≈ 10,0)	10^{-5}	$2 \cdot 10^{-7}$	10^{-6}	$2 \cdot 10^{-8}$	10^{-7}	$2 \cdot 10^{-9}$

Table B3: Tolerable lifetime failure probabilities (from [6] Table 2; [5] Table 6.1)

Based on Table B3 and the distribution and type of building premises he calculated the target probabilities for different building sizes.

Maximum number at risk in building	*N* number of fatalities			
	> 5	> 15	> 100	> 500
Less than 15	$5 \cdot 10^{-7}$	---	---	---
15 - 100	$1 \cdot 10^{-6}$	$3 \cdot 10^{-7}$	---	---
100 - 500	$2 \cdot 10^{-6}$	$5 \cdot 10^{-7}$	$6 \cdot 10^{-8}$	---
Greater than 500	$4 \cdot 10^{-6}$	$8 \cdot 10^{-7}$	$1 \cdot 10^{-7}$	$5 \cdot 10^{-8}$

Table B4: Target probabilities for fire risks in buildings and different size of building per year (from [5] Table B6)

In Table B4 $R_{acc,S}$ is not taken as a constant as simplified in equation (2b) but depends further on the number of persons at risk (e.g. number of persons in the building). Equation (2c) takes into account that $R_{acc,S}$ is not constant. Rasbash gives in this paper an example how to assess $R_{acc,S}$ ($N_{in\ building}$)

$$R_{acc,S}\ (N_{in\ building}) = p \cdot N_{fatality} \qquad (2c)$$

$N_{in\ building}$: numbers N of persons in building at time of fire
$N_{fatality}$: numbers N of persons killed by structural collapse due to fire

[1] The annual figures are based on a building lifetime of 50 years

However the target probability seem to be obviously more sensitive to the number of fatalities than to the number of persons at risk.

Figures B2 and B3 show some statistical data [5] of events with multiple fire death. There are very few incidents with more than 10 fire deaths in buildings.

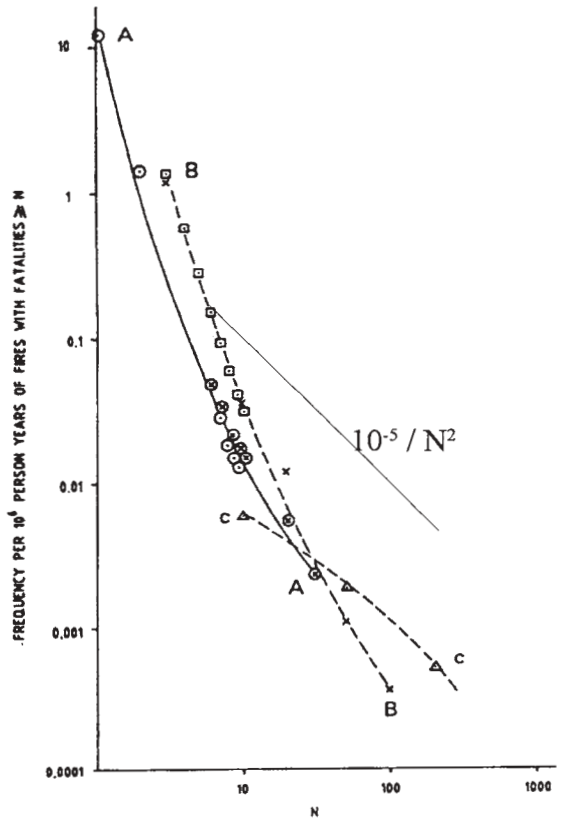

Figure B2: Multiple fatality fire and explosions in the UK and the USA

⊙ UK 1963 - 73
x USA 1970 - 82
⊡ USA 1977 – 82
⊗ UK 1960 – 82
△ USA WASH 1400

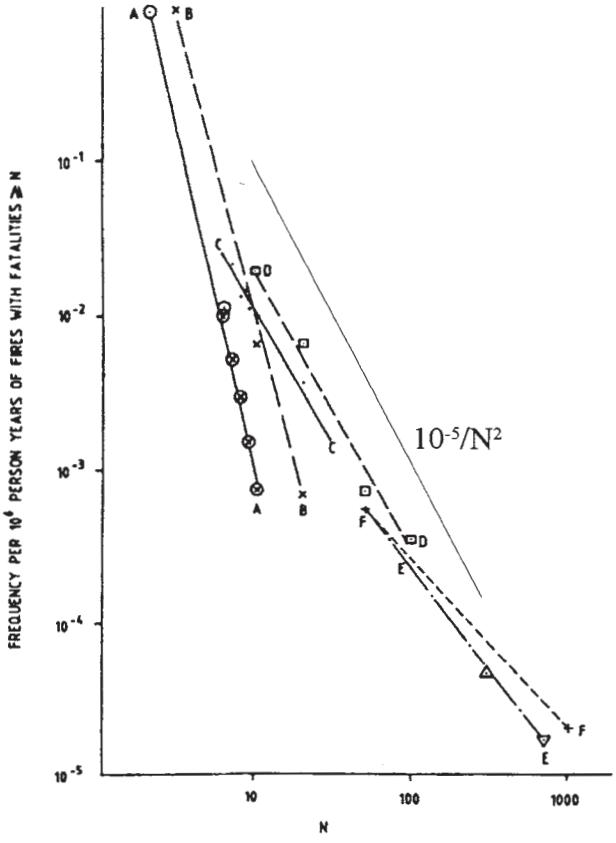

Figure B3: Multiple fatality fire in buildings only

Dwellings
⊙ UK 1963 - 73
⊗ UK 1960 - 82
x USA 1970 – 82

Not dwellings
· UK 1960 - 82
⊡ UK 1970 – 82
△ Rich world 1946 – 82
▽ Rich world 1883 – 1982
\+ all fires

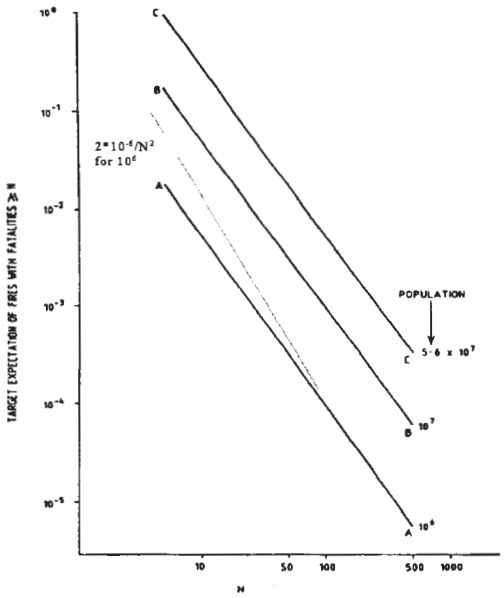

Figure B4: Proposed target for acceptability from multiple fatality fires in buildings other than dwellings from [5] and simplified curve for buildings other than dwellings with $2 \cdot 10^{-5} / N^2$ (assumption: 20% of fatalities occur not in dwellings i.e. $0{,}2 \cdot (10^{-5} / N^2)$)

2.4.2 Data by Kersken-Bradley (CIB W 14)

Kersken-Bradley et al. gave the following target probabilities for main structural members in the CIB W 14 – Design Guide [6]. The data by Rasbash is identical. This design guide has further led to the safety classes defined in the German DIN 18230 [8,9].

	Load bearing capacity						Insulation and integrity		
	Single storey			Multi-storey			Lifetime	Annual	N
	Lifetime	Annual	N	Lifetime	Annual	N			
Dwellings	10^{-4}	$2 \cdot 10^{-6}$	2,2	10^{-6}	$2 \cdot 10^{-8}$	22	10^{-4}	$2 \cdot 10^{-6}$	2,2
Schools	10^{-4}	$2 \cdot 10^{-6}$	2,2	10^{-5}	$2 \cdot 10^{-7}$	7	10^{-4}	$2 \cdot 10^{-6}$	2,2
Hotels	10^{-6}	$2 \cdot 10^{-8}$	22	10^{-7}	$2 \cdot 10^{-9}$	70	10^{-6}	$2 \cdot 10^{-8}$	22
Hospitals	10^{-6}	$2 \cdot 10^{-8}$	22	10^{-7}	$2 \cdot 10^{-9}$	70	10^{-6}	$2 \cdot 10^{-8}$	22
Homes for the elderly	10^{-6}	$2 \cdot 10^{-8}$	22	10^{-7}	$2 \cdot 10^{-9}$	70	10^{-6}	$2 \cdot 10^{-8}$	22
Theatres	10^{-7}	$2 \cdot 10^{-9}$	70	10^{-8}	$2 \cdot 10^{-10}$	224	10^{-7}	$2 \cdot 10^{-9}$	70
Shops	10^{-4}	$2 \cdot 10^{-6}$	2,2	10^{-5}	$2 \cdot 10^{-7}$	7	10^{-4}	$2 \cdot 10^{-6}$	2,2
Offices	10^{-4}	$2 \cdot 10^{-6}$	2,2	10^{-5}	$2 \cdot 10^{-7}$	7	10^{-4}	$2 \cdot 10^{-6}$	2,2
Industrial buildings	10^{-3}	$2 \cdot 10^{-5}$	0,7	10^{-4}	$2 \cdot 10^{-6}$	2	10^{-3}	$2 \cdot 10^{-5}$	0,7

Table B5: Hypothetical target failure probabilities; the example figures are lifetime and annual, unconditional failure (no fire given as starting point) probabilities for primary structural members.

- The annual figures are based on a building lifetime of 50 years.

Added to the values given by Kersken-Bradley is the expected number of persons involved in case of the failure of a structural member N, starting from an accepted individual risk of $1 \cdot 10^{-5}$ fatalities per person and year. This expected number of people involved in case of fire and collapse was calculated by using equation (2b), e.g. $R_{acc,S}$ = constant and $n = 2$, with C = number of persons involved N.
The acceptance criteria for integrity and isolation e.g. compartmentation is taken as the same as for single storey buildings.

2.4.3 DIN 18230

DIN 18230 [8] and [9] gives the following target failure probabilities of structural elements for different safety classes (consequences of failure increasing from Sk_b 1 to Sk_b 3 expected number of fatalities (low to high see 2.4.1) with equation (2a) the same consequences are found for multiple storey buildings as in Table B3)

fire safety class	DIN V 18230 (Sept. 1987) [8]		E DIN 18230 (May 1998) [9]	
	single-storey	multi-storey	single-storey	multi-storey
Sk_b 3	10^{-5}	10^{-6}	10^{-4}	10^{-5}
(2a) N =	1	10	0,1	1
(2b) N =	1	3,2	--	1
high requirements	($\beta = 4,27$)	($\beta = 4,77$)	($\beta = 3,72$)	($\beta = 4,27$)
Sk_b 2	10^{-4}	10^{-5}	10^{-3}	10^{-4}
(2a) N =	0,1	1	0,01	0,1
(2b) N =	--	1	--	--
medium requirements	($\beta = 3,72$)	($\beta = 4,27$)	($\beta = 3,09$)	($\beta = 3,72$)
Sk_b 1	10^{-3}	10^{-4}	10^{-2}	10^{-3}
(2a) N =	0,01	0,1	0,001	0,01
(2b) N =	--	--	--	--
low requirements	($\beta = 3,09$)	($\beta = 3,72$)	($\beta = 2,30$)	($\beta = 3,09$)
Probability of severe fore occurrence with fire brigade	$0,1 \cdot 2 \cdot 10^{-6} / m^2 \cdot year$ $= 0,2 \cdot 10^{-6} / m^2 \cdot year$		$0,1 \cdot 5 \cdot 10^{-6} / m^2 \cdot year$ $= 0,5 \cdot 10^{-6} / m^2 \cdot year$	

Table B6: Limit values for the failure probability p_f for industrial constructions according to DIN 18230 (reference period 1 year) and required reliability factors β. Added is the corresponding number of people involved in a structural collapse calculated by using equation (2a) and an individual risk of 10^{-5}.

The comparison between the 1987 and the 1998 version does not lead to a difference of 10 in the effective target value, because also the input data for fire occurrence and the fire brigade have been adapted.

2.4.4 Data from BSI DD 240 [10]

Based upon a simplification of the figures presented by Rasbash (see 2.4.1), who analysed UK fire statistics, the recommended risk criteria are given as:

a)	individual risk (per individual per year)		b)	risk of multiple deaths (per building per year)
	(1) at home:	$1{,}5 \cdot 10^{-5}$		(1) > 10 deaths: $5 \cdot 10^{-7}$ per building per year
	(2) elsewhere :	$1{,}5 \cdot 10^{-6}$		(2) > 100 deaths: $5 \cdot 10^{-8}$ per building per year

The use of the above figures would be expected to represent the current UK position, although other design criteria may be appropriate. They reflect the subjective risk perception of the public (see 2.3). The nature of fire-fighting activities is such that it is unlikely to be feasible to estimate quantitatively the risk to fire-fighters associated with a particular building.

2.5 Acceptance criteria for societal risks

For *environmental* risks (natural, industrial, transport hazards ...) with large consequences requirements have been established in various national regulations. With regard to human casualties Figures B5 and B6 give some examples of accepted occurrence frequencies of accidents as a function of the number of persons involved. As such codes deal with important societal risks which will concern authorities, usually only multiple death with $N \geq 10$ are considered. For typical single fatality events like car driving values of up to 10^{-4} seem to be tolerable by the public (see Table B1).

2.5.1 Dutch guidelines

Typical acceptance line for risks for hazards where the individual has little control over the activity (industrial hazards, transport of dangerous goods ...) are given in the **Dutch guidelines** and results from a risk analysis for an evacuation problem by Magnusson [11].

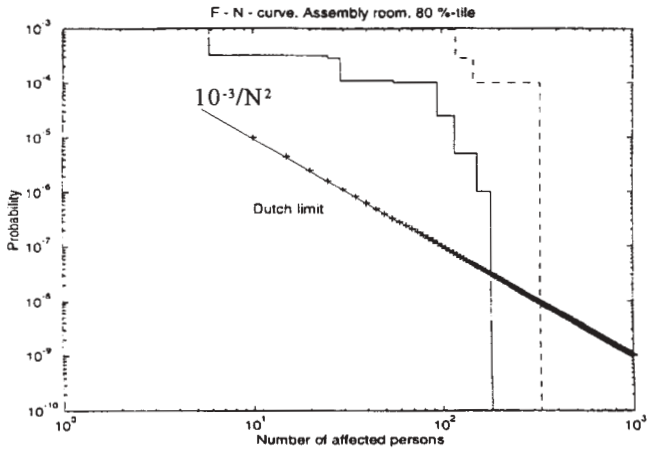

Figure B5: Typical acceptance line for risks (per year) for hazards where the individual has little control over the activity (industrial hazard, transport of dangerous goods ...) from Dutch guide-lines [12]

2.5.2 Swiss Handbook on environmental risks

Acceptance lines are also given in the Swiss Handbook I for Environmental hazards (Störfallverordnung 1991) [13]. The upper line of Figure B6 is the same as in Figure B5, the lower line gives 100 times smaller accepted frequencies per year of occurrence. The upper line must not be exceeded in any case the lower line is the zone of general acceptance. In between a reduction of risk is desirable, but dependant of the economical impacts.

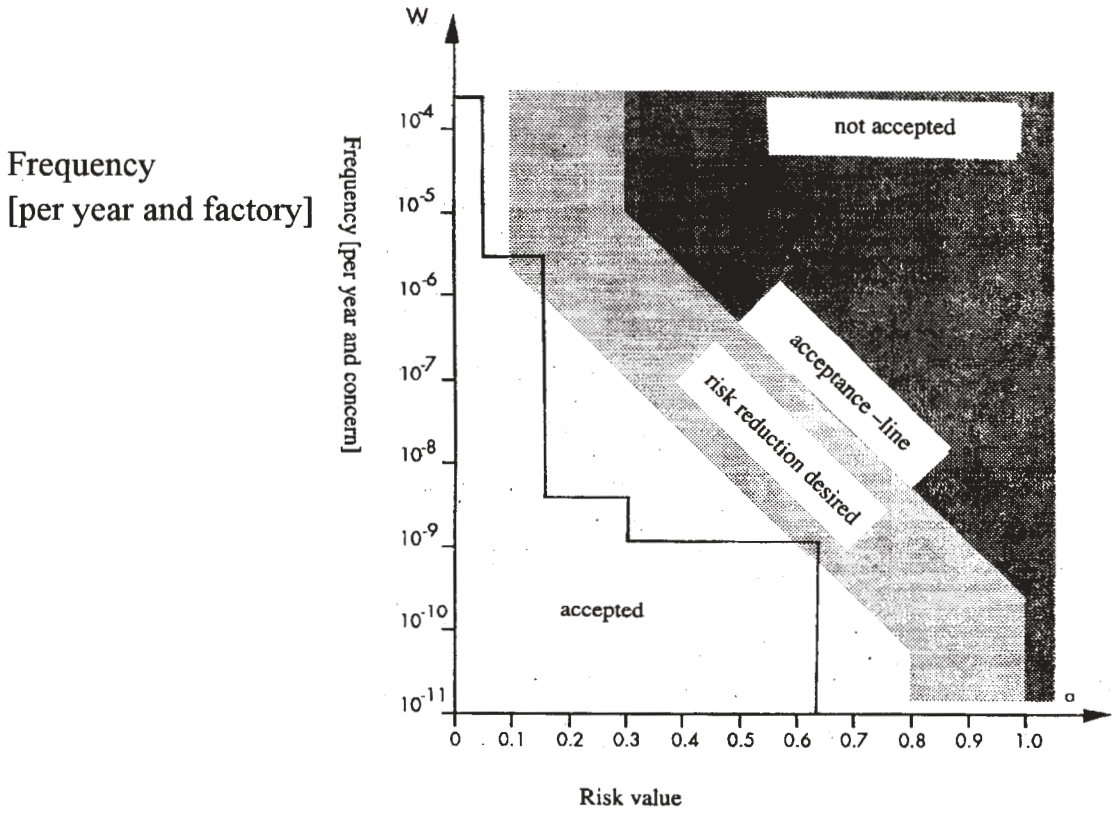

Figure B6: Acceptance lines according to Swiss Handbook I for Environmental hazards (Störfallverordnung 1991) [13] with typical risk steps

The risk value is mentioned to weight the consequences of a certain hazard . A risk value of 0,6 corresponds to the following consequences: 100 fatalities or 800 injuries or about 400 Mio CHF financial damage.

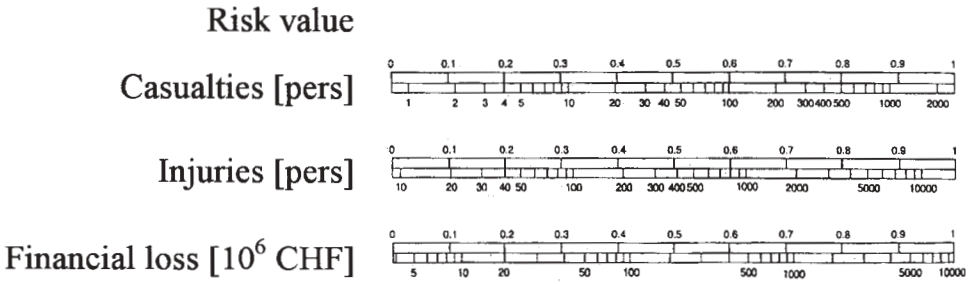

Figure B7: Risk value and the consequences according [13] Figure G.3

2.5.3 Data from UK for tolerability of risk from nuclear power stations

The UK Health and Safety Executive, HMSO [14], gives the following tolerable risk to individual member of the public.

Maximum tolerable risk to individual member of the public probability of death per year	General acceptable risk to individual member of the public probability of death per year
10^{-4}	10^{-6}

Table B7: Tolerability of risk

It is not related to the member of (multiple) fatalities in a single event.

The principle that a different design regime applies above around 10 fatalities is in accordance with Figure B4 and in Figure B5 upper limit. Both the "Dutch limit" and the Swiss limits fall approximately as $1/N^2$ below 10 fatalities.

2.6 Acceptance criteria for structural collapse

2.6.1 Eurocode 1: "Basis of Design and Actions on Structures"

In structural design at room temperature **EC1 part 1-1** (Annex A) [15] gives the following target probabilities (acceptable failure probability p_f of a main structural member e.g. a main beam)

	limit β	limit p_f
ultimate limit state condition	4,7	$1{,}30 \cdot 10^{-6}$
ultimate limit state serviceability	3	$1{,}35 \cdot 10^{-3}$

Table B8: Limit values for safety index β and failure probability p_f according to Eurocode 1, Annex A Table A.2 (reference period 1 year)

These values are reference values to calibrate design formulas rather than to describe actual frequencies of structural collapse.

The base value of a safety index of $\beta = 3{,}8$ for a building element gives a reliability of $7 \cdot 10^{-5}$ per life or $1 \cdot 10^{-6}$ / year based on a 70 year design life (Table B8 quotes $1{,}3 \cdot 10^{-6}$ based on a different design life). The base value relates to the design reliability of a building element with a moderate expected consequence of failure. Other suggested values from Eurocode background documents for other expected consequences of failure are:

Expected consequences of failure

Minor	Moderate	Large
Secondary/tertiary	Primary beam	Column
$0{,}7 \cdot 10^{-5}$ / year	$1 \cdot 10^{-6}$ / year	$1{,}5 \cdot 10^{-7}$ / year
$\beta = 4{,}3$ / year or	$\beta = 4{,}7$ / year or	$\beta = 5{,}1$ / year or
3,3 / life	3,8 / life	4,3 / life

2.6.2 Schneider

J. Schneider [16] discusses a reliability differentiation for cold design with respect to consequences and type of failure.

		Type of failure			
		Type A	Type B	Type C	Type D
Consequences	Class 1	1,0	1,5	2,0	2,5
	Class 2	1,5	2,0	2,5	3,0
	Class 3	2,0	2,5	3,5	4,0
	Class 4	2,5	3,0	4,5	5,0
	Class 5	3,0	4,0	5,0	6,0

Table B9: The following numbers may be taken as a rough indication of the order of magnitude for the target reliability indices β_0 *per year*. It should be noted that these numbers are bound to some specific assumptions concerning distribution types: e.g., log-normal for resistance, normal for dead loads, Gumbel for live loads. Also model uncertainties must duly be taken into consideration.

With respect to consequences, the following comments may help to identify applicable reliability indices:

- **Class 1:** Almost no consequences, small transient disturbances for users, serviceability affected during short periods
- **Class 2:** Minor consequences, no hazards to life and limb. Economic consequences of a failure are low (e.g., agricultural structures, glasshouses, etc.)
- **Class 3:** Moderate consequences, hazards to life and limb are low. Economic consequences of a failure are considerable (e.g., office buildings, etc.)

- **Class 4:** Large consequences, hazards to life and limb are medium. Economic consequences of a failure are very high (e.g., bridges, theatres, high rise buildings, etc.)
- **Class 5:** Extreme consequences, hazards to life and limb are high. Economic consequences of a failure are very high (e.g., power plants, large dams, etc.)

With respect to type of failure, the following comments may help to identify applicable reliability indices:

- **Type A:** Serviceability failure, structure almost in elastic domain
- **Type B:** Ductile failure of redundant systems with reserve strength
- **Type C:** Ductile failure, but almost no reserve strength
- **Type D:** Brittle failure of non-redundant systems

Ductile failure may be interpreted as being noticeable in advance by e.g. large deflections giving time for action (e.g. reduce loading, evacuate ...). Fire is also noticeable before collapse and could therefore be considered as type B or C.

The values from the Eurocode ($\beta_0 = 4{,}7$ per year see 2.6.1) compare well with values quoted for β_0 *per year* from Schneider in Table B9 for brittle failure mode type D. For those types of failure typical of steel structures which would be B (ductile with reserve of redundancy) and C (ductile with no reserve of redundancy) as follows:

Expected consequences of failure

Class 2	Class 3	Class 4
2,0 for B	2,5 for B	3,0 for B
2,5 for C	3,5 for C	4,5 for C

Comparing even the more onerous Type C failure, Schneider suggests $\beta_0 = 3{,}5$ per year compared with $\beta_0 = 4{,}7$ / year from the Eurocode background document. The target failure probability from Schneider would allow design failure more frequently for ductile failure.

The Eurocode values are, however, comparable with those given in Table B5 as follows:

- Primary structural member in multi-storey office: 2×10^{-7} / year (as column)
- Primary structural member in single storey office: 2×10^{-6} / year (as beam)

Values for industrial buildings in Table B5 are 10 times higher reflecting occupancy levels that are, say, 10 times lower per m^2.

2.7 Acceptance criteria for structural collapse in case of fire

A proposal on how to establish an acceptance criterion for structural collapse in case of fire based on fire statistics is given below for discussion:

2.7.1 Accepted individual risk to life

From fire statistics the number of fire casualties in industrialised countries is between 0,4 to 2,0 per 10^5 inhabitants and year (see Table B1 and [3]). As there seems to be no general concern in society about fire risk being too high an average value of

$$R_{acc,Ind.} = 1 \cdot 10^{-5} \cdot \frac{\text{fatalities per year}}{\text{person at risk}} = 10^{-5} \cdot \frac{\text{fatalities per year}}{\text{inhabitant}}$$

seems to be an accepted individual fire risk. The group of persons at risk in national fire statistics is usually taken as all inhabitants of a country. For the design of a building specific information on the building may reflect the number of persons in the building.

2.7.2 Accepted subjective risk to life in case of fire

In case of multiple death the societal risk concerns authorities and society. By applying the same limits for fire as for environmental risks (see 2.5). The probability of a fire killing N persons should in no case exceed

$$p_{acc} \le 10^{-3}/N^2 \quad \text{[(fatalities per year) / habitant] or simplified [1 / year]} \quad (3a)$$

and should be limited if economically feasible to

$$p_{acc} \le 10^{-5}/N^2 \quad \text{[(fatalities per year) / habitant] or simplified [1 / year]} \quad (3b)$$

N: is the expected number of fatalities in a fire (For N<1 p_{acc} should be taken as 10^{-3} in (3a) resp. 10^{-5} in (3b)).
Equation (3a) corresponds to the Dutch acceptance line in Figure B4. Equation (3b) is close to the lower line in Figure B5. The lower limit (3b) seems appropriate for fire design. With regard to equation (2b) this corresponds to n = 2, p = 10^{-3} (3a), respectively p = 10^{-5} (3b) and c = number of expected fatalities.

Equation (3a) and (3b) consider that the society is risk averse, and it is generally true that societies are averse to the risk of multi-fatality accidents where the number N of persons affected is more than 10. In the range from N = 1 to 10 it is often a reasonable assumption that n = 1 can be used in equation (3a) and (3b). In applying these principles to the design of steel structures, it should be noted that it is extremely unlikely that any fire in a steel structure would lead to a 100-fatality accident. Hence it is suggested that two design regimes be considered:

- The design regime for building elements and compartments that would put up to 10 persons at direct risk. For example, it might be assumed that an office contained 1 person per 10 m^2 of space, and this accords with a compartment of around 100 m^2. The support structure for this area would typically use about 50 tonnes of steel. In this design regime it could be assumed that n = 1 in equation (3b), and the probabilistic methods outlined in this document can be applied.
- The design regime for whole frames that would put more than 10 persons at risk should be treated differently. In effect, society wishes such events to be so unlikely as to be practically impossible. Values of less than 10^{-6} per annum for the whole society are cited for such extreme scenarios. In practice this means that the designer needs to be satisfied that no fire scenario could lead to such an extreme multi-fatality event. To achieve such low levels of risk requires high levels of functional reliability that can only be provided by providing safety by more than one route. Accepted practice in fire safety design reflects this principle as it provides, for example, compartmentation, alarms, smoke venting, active/passive fire protection, and professional fire brigades.

2.7.3 Accepted individual risk to life due to structural collapse in case of fire

From statistics we know that most fire fatalities occur due to smoke and heat and not because of structural collapse. Therefore only part of the accepted risk to life in case of fire may be allowed due to structural collapse. Assuming 1 % of all fire death are due to structural collapse, the accepted individual risk to life due to structural collapse in case of fire becomes

$$R_{acc,\,Ind,struct,fi} = \frac{0{,}01 \text{ fatalities per year}}{10^5 \text{ inhabitants}} = 1 \cdot 10^{-7} \frac{\text{Fatalities per year}}{\text{inhabitant}}$$

2.7.4 Conditional and unconditional failure probability

2.7.4.1 General

For the failure probability of a structural element two cases have to be clearly separated:

- the structural failure probability given a severe fire (conditional failure probability) p_f, and
- the structural failure probability starting from a fire free status (unconditional failure probability) $p_{f,fi}$

$$p_f = p_{severe,fire} \cdot p_{f,fi} \text{ [(fatalities per year) / habitant]} \quad (4)$$

2.7.4.2 Occurrence frequency of severe fires

From the statistics of 40.000 fires in Bern [17] the probabilities that fires will grow to a severe fire endangering the structures can be taken from Table B9 of this NFSC report. On the basis of a loss of 50.000 CHF as an indicator for a severe fire the following probabilities of occurrence $p_{severe,fire}$ are found:

- Office / Public $0,4 \cdot 10^{-6}/m^2 \cdot yr$
- Dwellings $0,7 \cdot 10^{-6}/m^2 \cdot yr$
- Industrial $1,32 \cdot 10^{-6}/m^2 \cdot yr$
- All fires $0,93 \cdot 10^{-6}/m^2 \cdot yr \approx 1 \cdot 10^{-6}/m^2 \cdot yr$

This data corresponds to the values for severe fires in industrial buildings with public fire brigade (reduction factor $p_2 = 0,1$) given in DIN 18230 (1998) [9].

DIN 18230 (1998) [9] gives $p_{severe,fire} = 5 \cdot 10^{-6} \cdot 0,1 = 0,5 \cdot 10^{-6}/m^2 \cdot yr$

2.7.5 Accepted unconditional failure probability of a structural member

The risk to life due to structural collapse of a member is

$$R_{struct,fi} = p_f \cdot N \text{ [fatalities / year]} \quad (5)$$

p_f : frequency of structural collapse = $p_{severe,fire} \cdot p_{f,fi}$
N : number of persons killed in case of structural collapse due to fire

Since people evacuate in case of fire N will decrease with time.

With regard to life safety the risk due to structural collapse of a member should not exceed the accepted individual risk given in 2.7.3 (e.g. $1 \cdot 10^{-7}$ fatalities per year and inhabitants).

To compare the calculated risk $R_{struct,fi}$ to the individual risk $R_{acc,Ind,struct,fi}$ (see 2.7.3) we have to define the number of persons at risk in the building.

2.7.5.1 Simplified approach

Assuming that the density of people is the same in all buildings and the failure probability of all structural members are the same then the individual risk could directly be applied as an accepted limit

$$R_{struc,fi} = p_f \cdot N \leq R_{acc,\,Ind} = 1 \cdot 10^{-7} = p_{f,acc} \cdot N$$

and the accepted unconditional failure probability becomes

$$p_{f,acc} \leq \frac{1 \cdot 10^{-7} \cdot \text{fatalities per year}}{N \text{ [fatalities in case of collapse]}} \leq 1,0 \quad (6)$$

To take into account multiple fire death N could be replaced by N^2 (for $N > 1$).

2.7.5.2 Comparison of simplified approach to EC1 part 1-1 Annex A [2]

EC1 part 1-1 Annex A gives for a main structural member a typical accepted failure probability of $p_{f,acc} = 1,3 \cdot 10^{-6}$ / year. Assuming that this figure covers the governing action combination applied for any hazard and a main structural element with brittle failure mode (e.g. no evacuation before collapse) and that the objective of this limit is life safety, then for the case of fire the following accepted failure frequency could be estimated taking into account evacuation.

In fire people will evacuate reducing the expected number of fatalities by say a factor of 100 under normal conditions (e.g. mobile persons) and 10 (e.g. handicapped or sleeping persons) for difficult evacuation.

$$p_{f,acc,fi} = 1,3 \cdot 10^{-6} \cdot 1 \quad = 1,3 \cdot 10^{-6} \qquad \text{(no evacuation)} \tag{7}$$

$$p_{f,acc,fi} = 1,3 \cdot 10^{-6} \cdot 10 \quad = 1,3 \cdot 10^{-5} \qquad \text{(difficult evacuation)} \tag{8}$$

$$p_{f,acc,fi} = 1,3 \cdot 10^{-6} \cdot 100 \quad = 1,3 \cdot 10^{-4} \qquad \text{(normal)} \tag{9}$$

This is consistent with the data given in DIN 18230 (see Table B6) for multi-storey buildings (difficult evacuation) and single storey building (normal evacuation) and high requirements (SK_b 3).

2.7.5.3 With consideration of the number of people in the building

Taking the average number of people in the building as a basis we can compare their risk to the accepted individual risk or to that related to a specific group of buildings (see e.g. 2.4.5).

$$R_{Ind,fi} = p_{f,acc} \cdot \frac{N\,[\text{fatalities}]}{N\,[\text{people in building}]} \le R_{Ind,acc} \tag{10}$$

or

$$p_{f,acc} \le R_{Ind,acc} \cdot \frac{N\,[\text{people in building}]}{N\,[\text{fatalities}]} \tag{11}$$

The conditional failure probability p_f has to be calculated for a specific design situation was the expected number of fatalities and people in the building are input data. This data is related to the type of occupancy and construction of the building.

Note:

The conditional (given severe fire) failure probability would be found as:

$$p_{f,fi,acc} = p_{f,acc} / p_{severe,fi}$$

2.8 Simplified acceptance criteria of structural failure probability in case of fire

2.8.1 Engineering approach

In a design process the number N of fatalities in case of the collapse of a structural member due to fire is first estimated. In a second step the tolerable failure probability is calculated as follows:

On the basis of the risk to life expressed by the expected number of fatalities N due to structural collapse in case of fire, the accepted failure probability of an element can be chosen as

$$p_{f,acc} \leq 1 \cdot 10^{-7} / N^2 \quad \text{for } N > 1$$

$$\leq 1 \cdot 10^{-7} / N \quad \text{for } N \leq 1$$

where: - $p_{f,acc}$ is the unconditional failure probability (see 2.7.4)

i.e. $p_{f,acc} = (p_{severe\ fire} \cdot A) \cdot p_{f,fi}$

- $p_{severe\ fire}$: (see 2.7.4.2)
- $p_{f,fi}$: probability of structural failure given a severe fire
- A : Area of the compartment in fire

Note: because of evacuation N will in many cases become 0.

In a third step the element is designed to this criterion and from the failure time it is verified that the number of fatalities is in accordance with the first estimate. The design process may need iteration.

2.8.2 Simplified approach

This design process does only estimate the proportion of people evacuating before structural collapse (0%, 90%, 99%). It is less accurate then the method in 2.7.1 but does avoid an estimate of the number of persons killed in case of structural collapse and an iterative process.

For a main element e.g. a beam and on the basis of a comparison between the general acceptance criterion given in Annex A of EC1 part 1-1 [2] and the fire situation (see 2.7.5.2) the accepted failure probability per year of a structural member would roughly be taken as:

$p_{f,acc} = 1{,}3 \cdot 10^{-4}$ for normal
$p_{f,acc} = 1{,}3 \cdot 10^{-5}$ for difficult evacuation (hospitals, etc.)
$p_{f,acc} = 1{,}3 \cdot 10^{-6}$ for no evacuation.

Note: $p_{f,acc}$ is the unconditional failure probability (see 2.7.4).

The conditional failure probability $p_{f,fi}$ (i.e. structural failure given severe fire) becomes

$$p_{f,fi,acc} = p_{f,acc} / (p_{severe\ fire} \cdot A) \qquad \text{with } p_{severe\ fire} \approx 1 \cdot 10^{-6}/m^2 \cdot year$$

e.g. $p_{f,fi,acc} = 130 / A$ for normal
$p_{f,fi,acc} = 13 / A$ for difficult evacuation
$p_{f,fi,acc} = 1{,}3 / A$ for no evacuation

where: Area of fire compartment A in [m^2]
$p_{f,fi,acc}$ [1 / year]

or for multiple death

e.g. $p_{f,fi,acc} = 130 / (A \cdot N^2)$ for normal
$p_{f,fi,acc} = 13 / (A \cdot N^2)$ for difficult evacuation
$p_{f,fi,acc} = 1{,}3 / (A \cdot N^2)$ for no evacuation

where: Area of fire compartment A in [m^2]
N [fatalities]
$p_{f,fi,acc}$ [1 / year]

These values correspond to a main beam. For the columns of multi-storey buildings $p_{f,fi,acc}$ could be divided by a factor of 10, for secondary elements it could be multiplied by 10.

3 DETERMINISTIC APPROACH

The deterministic approach starts from a given scenario or from characteristic values for the input data and uses a specific calculation model. For "cold" structural design input data, safety factors and models are found in codes (e.g. Eurocodes, national codes of practice). The results of the analysis are then compared to limit states (e.g. ultimate, serviceability, tenability etc.).

3.1 Uncertainties and safety factors

Uncertainties when establishing the worst case scenarios are found :
- in the input data (fire load, ventilation conditions, place of ignition ...)
- in the calculation procedure
- in the consequences of failure

Uncertainties can be addressed by conservative assumption of the characteristic input data or by the addition of safety factors.

3.2 Limiting conditions for tenability

Limiting conditions for life safeties are:
- toxic products (chemical product, concentration, time of exposure)
- heat (Radiation, Temperature, time of exposure)
- visibility (distance at specific height)

Data is given in literature e.g. DD240 [10], however the models and characteristic values were not as well established as in cold design.

This WG5 document combined with the WG4 report "Statistic" describes the methodology to determine the factor γ on the fire load and concludes by giving values for γ_{q1} considering the area of the fire compartment, γ_{q2} the occupation type of the building and γ_{ni} the active fire fighting measures.

4 COMPARATIVE APPROACH

4.1 General

The direct evaluation of a target probability as well as the analysis of the probability of failure are dependent on uncertain data, models and assumptions made. An advisable alternative approach is the calibration to existing practice established in codes:
- design a set of typical structures or elements complying with existing codes
- calculate reliability index β_0

Between different examples according to codes β_0 will vary and a target value β_0 will have to be chosen within acceptable bounds.

4.2 Comparison to prescriptive design

For a performance based fire safety concept the target reliability can be found by comparison to a code complying design:

1a) design structural element (or structure) complying to code requirements
1b) calculate reliability β_0

2a) design structural element performance based
2b) calculate reliability β

3) compare $\beta \geq \beta_0$

By making the same assumptions on variables etc. and using the same models for calculation β_0 and β most of these assumption will cancel each other out.
Further information will be found from the α-values given by a FORM analysis indicating the dominant variables.

4.3 Example

As an Example a beam in an office is considered as given in Figure B8. The code design R60 is compared to an unprotected beam with sprinkler protection in the room.

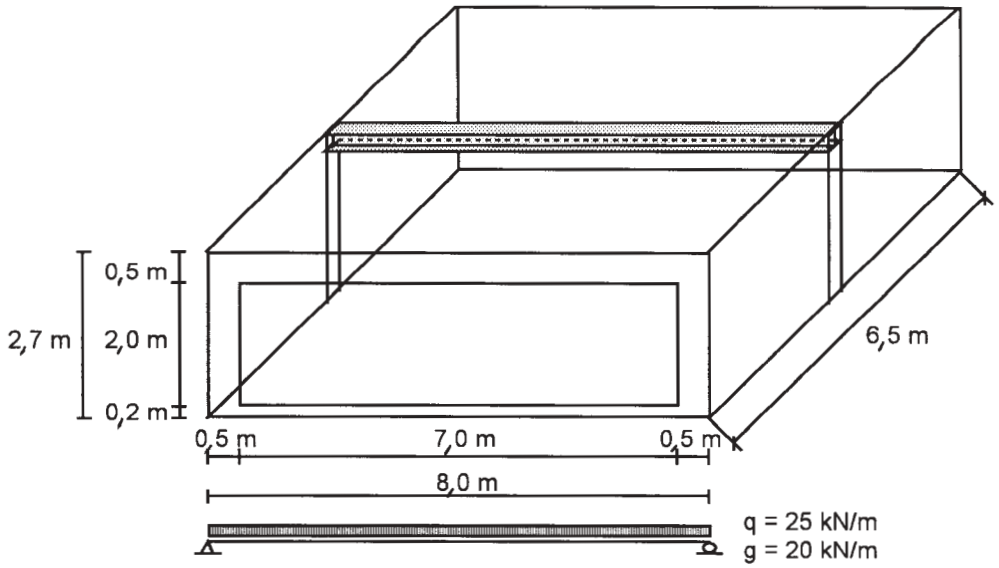

Figure B8: Example office room with steel beam and statical system and characteristic load

4.3.1 Statical system and load

The statical system and load are given in Figure B8. The design value of the load for room temperature design is:

$q_d = 1{,}3 \cdot 20\ kN/m + 1{,}5 \cdot 25\ kN/m = 63{,}5\ kN/m$

4.3.2 Ultimate limit state for an IPEA 550 S235 (M_{pl} = 583 kNm)

$M_d = 63{,}5 \cdot 8^2/8 = 508 < M_{Rd} = 583\ kNm/1{,}1 = 530\ kNm$

4.3.3 Fire resistance (ISO fire)

The design value of the load in fire (according to SIA 160) [18] is:

$q_{d,acc} = 1{,}0 \cdot 20\ kN/m + 0{,}3 \cdot 25\ kN/m = 27{,}5\ kN/m,$
$M_{d,acc} = 27{,}5 \cdot 8^2/8 = 220\ kNm\ ;\ \eta = 220/583 = 0{,}38$

- The critical temperature and ISO-fire resistance of unprotected beam with $A_m/V = 143$, and $\kappa = 0{,}7$ is:
- $\Theta_{crit} = 690°C\ ;\ t_R = 21$ Min [19]
- For R60 ISO-fire resistance a protection with fibre silicate plates ($\lambda = 0{,}15$ W/(m·κ) of 7,5 mm thickness and a concrete slab on the top ($A_p/V = 111\ \kappa = 1{,}0$) would be necessary [1]

4.3.4 Behaviour under natural fire conditions

The time temperature curve is calculated for the following conditions:

- The office geometry as given in Figure B8. (All bounding surfaces are made of 12 cm normal weight concrete).
- The window, assumed to be 85 % broken and the door closed.
- Fire load consisting of wood type fuel with a RHR of 250 kW/m^2 and a 80 % efficiency of burning. The fire load is Gumbel distributed with $q_{80\%}$ = 570 MJ/m^2.

The results of a temperature simulation with a zone model [20] show:

- for the design fire load of 570 MJ/m^2 a maximum steel temperature of 760°C is reached for the unprotected and 445°C for the protected beam.
- the critical temperature of 690°C is reached for q = 380 MJ/m^2 for the unprotected and for q = 1450 MJ/m^2 for the protected beam.

4.3.5 Reliability

- A Form analysis shows that for a given opening the fire load is the dominant variable with an $\alpha > 0{,}9$.
- From the CDF of the fire load the following fractiles can be found:
  $F(380\ MJ/m^2) = 0{,}48$, $F(1450\ MJ/m^2) = 0{,}9994$.
- As a simplification the fuel load is taken as the only variable ($\alpha > 0{,}9$), thus giving the conditional ('given a severe fire') failure probability as:

$$p_{f,Fo} = [1 - F(q_{crit})]$$

q_{crit}: Fire load leading to the critical steel temperature
$F(q_{crit})$: CDF of q_{crit}
$p_{f,Fo} = [1 - F(380\ MJ/m^2)] = 0{,}52$ (unprotected beam)
$p_{f,Fo} = [1 - F(1450\ MJ/m^2)] = 0{,}0006$ (protected beam)

- The probability of a severe fire in an office is found to be $0{,}4 \cdot 10^{-6}/m^2 \cdot year$ [17] on the basis of statistics.
- Assuming that the fire protection will be defective in 2% of the time the failure probability of the code complying R60 beam is :

$$p_{f,R60} = 52\ m^2 \cdot 0{,}4 \cdot 10^{-6}/(m^2 \cdot year) \cdot [0{,}0006 + (0{,}02 \cdot 0{,}52)] = 0{,}22 \cdot 10^{-6}/yr$$

- The probability of sprinklers not stopping a fire to become severe is assumed from the statistics on sprinklers to be $\leq$ 2% [17]. The probability of failure of the unprotected beam is therefore:

$$p_{f,sp} = 52\ m^2 \cdot 0{,}4 \cdot 10^{-6}/(m^2 \cdot yr) \cdot 0{,}02 \cdot 0{,}52 = 0.21 \cdot 10^{-6}/yr$$

4.3.6 Acceptance

- Both concepts have a level of reliability higher than the acceptance criteria of the Eurocode 1 Annex A of $p_{accepted,structural} = 4 \cdot 10^{-5}$ as discussed in chapter 3.2.
- The alternative sprinkler concept has about the same reliability as the code complying structural concept.
- However one has to note that changes in the assumptions made can influence the results of the analysis markedly (e.g. ventilation conditions, RHR reliability of sprinklers or reliability of protective cladding etc.).
- Further sprinklers have other benefits on life safety than just increasing structural reliability (e.g. reduction of heat and smoke production, alarm to the fire brigade etc.). Therefore the results of such a partial analysis have always to be but into the context of a global fire safety analysis when developing a performance based fire safety analysis.

5 RESCUE OR PREVENTION COST

Rescue cost CHF per saved life	
100	Multi-vaccination 3rd world
$1 \cdot 10^3$	
$2 \cdot 10^3$	x-ray unit
$5 \cdot 10^3$	Helmets for motor-cyclists
$10 \cdot 10^3$	Cardio-ambulance
$20 \cdot 10^3$	Periodical checks for tuberculosis
$50 \cdot 10^3$	Rescue helicopter
$100 \cdot 10^3$	Seat belts in cars
	Refurbishment of crossings and structural systems
	Kidney dialysis
$500 \cdot 10^3$	Reinforcement for earth quakes
$1 \cdot 10^6$	
$2 \cdot 10^6$	
$5 \cdot 10^6$	Security suburban railway Zurich
$10 \cdot 10^6$	Earth quake code SIA 160
$20 \cdot 10^6$	Safety standards in mines USA
$50 \cdot 10^6$	Improve safety standard of DC 10
$100 \cdot 10^6$	High rise building code GB
$1 \cdot 10^9$	Asbestos refurbishment of schools

Table B8: Rescue cost

This method can be used to evaluate if a certain measure is justified by calculating the cost to save one live per year with that method. It is intended to show which measure is the most efficient in saving life. It is more likely to find acceptance by the authority then the definition of accepted failure probabilities or death per year. The method is described by Schneider J. [21] (German version of the book page 147 ff. This chapter is not found in the English version [16] of the book).

Example: Cost of battery driven smoke-detectors in private homes

Assumption for the example:
With home detectors in every apartment half of the fire death at home would be avoided, if 1 detector per Person would be installed in each apartment. With a life time of the detector of 10 years, cost for a detector 50 CHF and cost for the battery 3 CHF per year the cost per detector and year would be 8 CHF per year.

Number of fire death at home (Switzerland) 4 per 10^6 persons/year
Number of persons saved per year: 2 persons per 1.000.000 inhabitants
Cost of detectors per year and 10^6 persons: 8.000.000 CHF
Rescue cost: 8.000.000 CHF / 2 life saved = $4 \cdot 10^6$ CHF per life saved

A comparison to the rescue cost of other safety measures or examples given in Table B8 for other areas allows to evaluate the efficiency of this measure.

6 SYSTEMS APPROACH

6.1 Steps in the design process

A quantitative performance-based approach needs at least the following steps:

1. Hierarchical ordering of the building process and fixing of objectives against the background of codes and clients requirements (Figure B8)

2. Identifications of hazards and important fire scenarios (Figure B9)

3. Design of fault trees showing the key routes to failure

4. Identification of probabilities and consequences for each of the branches (Figure B10)

5. Comparison of the risk against accepted risk for the possible consequences (Figure B11)

6.1.1 Hierarchical ordering

Figure B9 is based on the Swiss Code of practice SIA 160 (1989) [18] and described by J. Schneider [16].

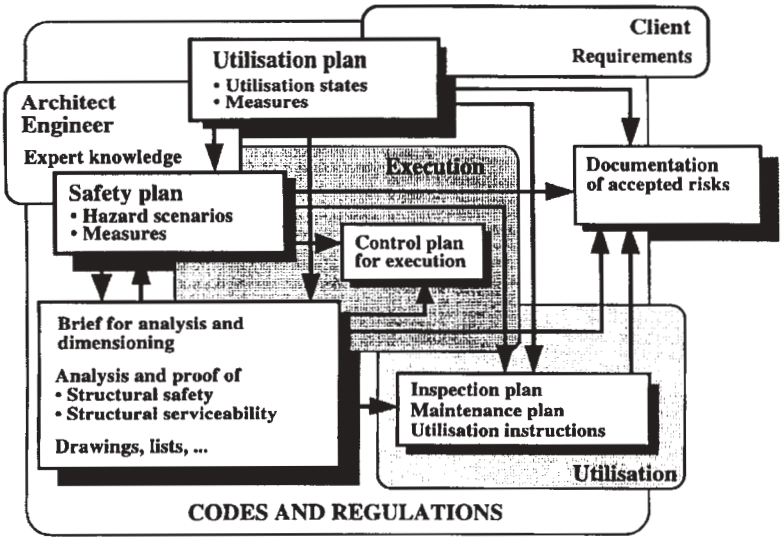

Figure B9: Hierarchical ordering of building process and fixing of objectives [16]

Applying the principles outlined in Figure B1 to the design of steel structures in fire will need to include the following important factors:

- The clients requirements are key for the utilisation plan. The utilisation plan is an important source for the identification of hazards and the feasibility of possible measures. The safety plan is worked out by the fire safety engineer on the basis of the building lay-out and the utilisation plan. The safety plan should be checked against expert knowledge.
- The **expert knowledge** should draw on other specialists as well as the architect, structural engineer, the fire brigade representative, building control officer and safety management consultant. This is the core of what is termed the Qualitative Design Review (QDR) in some codes of practice.
- The **inspection and maintenance plan** of the building includes all measures that are critical to assessing the likelihood of failure for active fire prevention / protection systems (e.g. alarms, smoke curtains, sprinklers) and for passive systems (e.g. Fire doors, fire dampers, claddings).
- The likely consequences of failure would be influenced by the **utilisation instructions** such as the fire safety management regime to be operated by the client (e.g. continuously manned emergency centre, staff training as fire wardens, use of night watchmen, good house-keeping e.g. control of fire load, fire exits...). A fire safety manual would document these instructions.
- The **control plan for execution** would include the quality control measures for the installation of passive fire protection measures and for the commissioning of active prevention/protection systems.
- The **documentation of accepted risks** would summarise the fire safety objectives, the accepted criteria, the trial fire safety designs, and fire scenarios analysed.

6.1.2 Identification of hazards

From Figure B10 it is clear that uncertainties and errors in quantifying **the objective hazard potential** generally contribute the largest proportion of the **residual risk**. This matches the general experience of building failures that originate more often from human errors in design than from variations in manufacturing or construction. Hence, it is important to take active steps to reduce such hazards from human errors as much as possible. The pooling of expert knowledge in the QDR process is the main method used in fire engineering, if necessary using experts of like discipline to provide "peer review" of decisions.

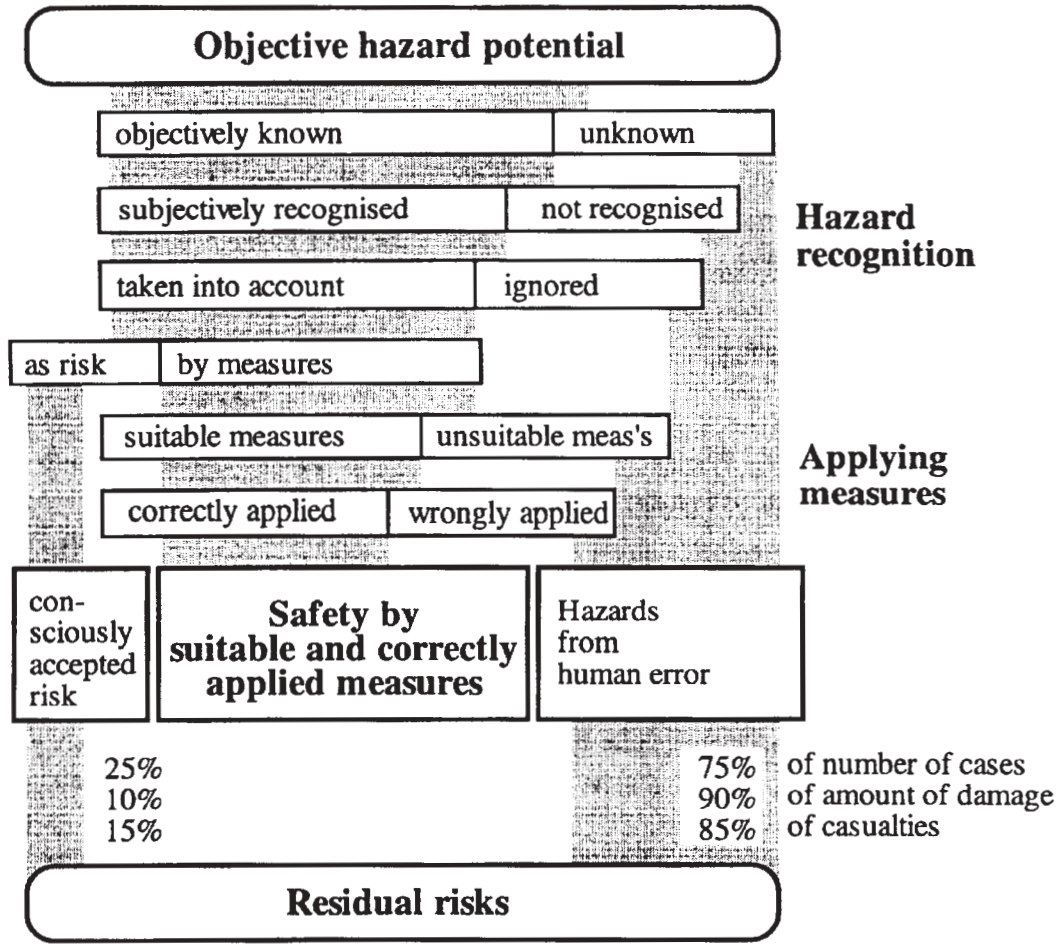

Figure B10: Hazard potential and residual risk [16] and [22]

6.1.3 Routes of failure and consequences

The application of Figure B11 can be extremely time-consuming if steps are not taken to identify and concentrate on the most likely faults and events. Again the use of expert knowledge in the QDR is the main method for focussing on the most relevant fire scenarios to analyse.

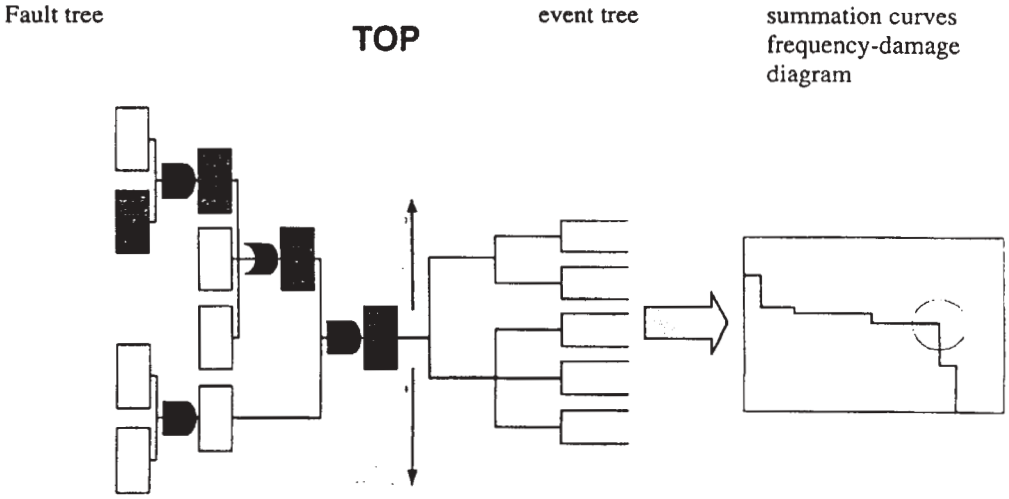

Figure B11: Risk analysis and visualisation process using logic trees and frequency-damage diagrams []

6.1.4 Risk assessment

It is now generally accepted in risk assessment that the term **hazard** applies to something with the potential to cause harm (i.e. the *cause*), and the term **risk** is used to express the likelihood that the harm from a particular hazard is realised (i.e. the *effect*). In applying Figure B12, the **risk analysis** needs to identify the likelihood and severity of the outcomes arising from the **hazard potential**.

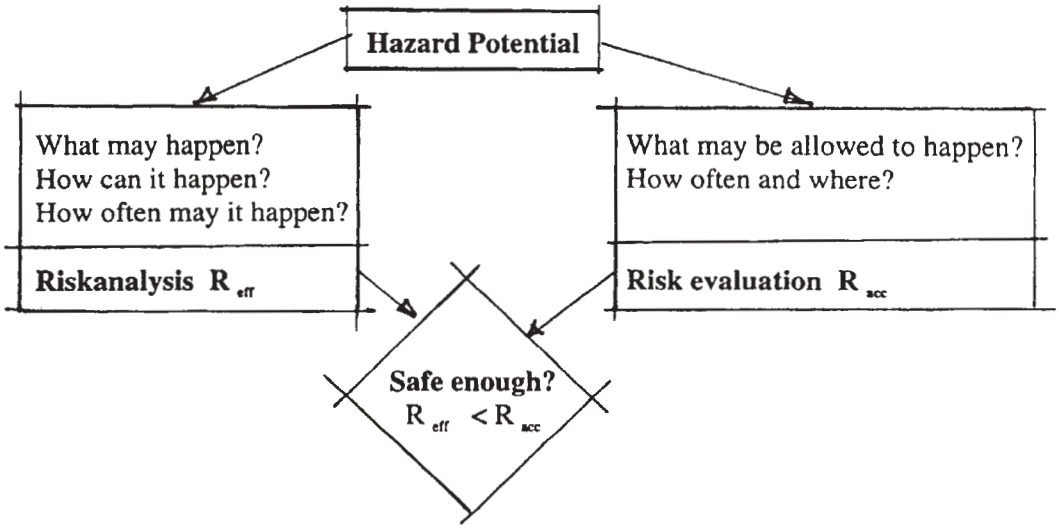

Figure B12: Risk analysis and risk evaluation

Definitions and methods are described by **J. Schneider** [16].

Risk assessment is one step in risk management, and this can be seen in the example of using compartmentation as a fire control measure. This is aimed specifically at limiting the severity of the fire to a defined area for long enough to avoid all the building occupants being put at risk from a fire ignition hazard arising in one compartment.

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ANNEX BB - EXAMPLE FOR THE DESIGN APPROACH

For the beam given in chapter 4.3 the design approaches described in chapters 1.2 and 1.3 can be illustrated as follows:

a) Prescriptive approach

The prescriptive design code would prescribe that for an office with a span from 5 to 8 m beams HEA 400 S235 should be spaced not more than 3,5 m.

The IPE A 550 (92,1 kg/m') would have to be replaced by the heavier HEA 400 (125 kg/m').

b) Deterministic approach

Characteristic data for actions and safety factors are taken from a design code, as well as the resistance models and materials data. The procedure based on Eurocode 1 [15] and 3 [24] is as follows:

Structural system and loads:

Beam:	Length:	ℓ	= 8,0 m
	Self weight:	P	= 20 kN/m
	Imposed load:	N	= 25 kN/m

Load level for cold design
The design load at room temperature is calculated to:

$q_d = \quad 1{,}35 \cdot P + 1{,}5 \cdot N = 1{,}35 \cdot 20\ kN/m + 1{,}5 \cdot 25\ kN/m = 64{,}5\ kN/m$

$$M_d = \frac{q_d \cdot \ell^2}{8} = \frac{\mathbf{64{,}5 \,.\, 8^2}}{\mathbf{8}} = 516\ kNm$$

Deterministic design resistance for room temperature

IPE A 550 (S235) with	A	= 11700 mm^2
	I_y	= 671,2 · 10^6 mm^4
	Z_y	= 2480 mm^3
	f_y	= 235 N/mm^2

$R_d = M_d = f_y \cdot Z = 235 N/mm^2 \cdot 2480 mm^3 = 583{,}0\ kNm$

S_d	≤	R_d / γ_R
516 kNm	≤	583,0 / 1,1 = 530,0 kN

The IPE A 550 S235 fulfils the limit state (acceptance) criterion $M_d < M_{Rd}$. The deflection is here not considered.

c) Probabilistic approach

Input data is not taken as characteristic data but as variables.

Probability density function (PDF) for each variable (cold)
Self weight:
P: law: Gaussian
nominal value : 50% fractile = 20 kN/m
$V_Q = 0,1$
$m_Q = 20$ kN/m
$\sigma_Q = m_Q \cdot V_Q = 2$ kN/m

Variable load:
N: law: Gumbel Type I
nominal value : 95% fractile = 25kN/m
$V_N = 0,3$
$m_N = 25$ kN / 1,56 = 16 kN/m
$\sigma_N = m_N \cdot V_N = 4,8$ kN/m

Structural steel:
R: law: lognormal
nominal value : 95% fractile = 235 N/mm^2
$V_R = 0,052$
$m_R = e^{1,645VR}$*235 N/mm^2 = 255,987
$\sigma_R = m_R \cdot V_R = 13,3$

Probabilistic design resistance

	nominal	fractile	m	σ	V	Law
P	20	50%	20	2	0,1	N
N	25	95%	16	4,8	0,3	GL
R	235	95%	255,987	13,3	0,052	LN

The limit state function is defined as followed:

$$G = R_{pl} - \left(\frac{(N+P) \cdot l^2}{8}\right) = f_y \cdot Z - \left(\frac{(N+P) \cdot l^2}{8}\right) = (f_y \cdot Z)/1000 - ((N+P) \cdot L\text{^}2)/8$$

Variables of G:

L	D	8,000	
W	D	2,480e+03	
N	GL	13,840	0,267
P	N	20,000	2,000
f_y	LN	5,544	0,052

FORM Analysis of G:
IPE A 550 S235 β = HL - Index = 4,25 p(G<0) = 1,06 · 10^{-5}

For the beam a failure probability of $1{,}06 \cdot 10^{-5}$ was found. The Eurocode design process ([15] and [23]) assumes implicitly that the failure probability of the structure p_f is lower than the target failure probability of $7{,}25 \cdot 10^{-5}$ per working life of the building, which is equivalent to a safety factor $\beta = 3{,}8$. This value of 3,8 for the ultimate limit state target probability index is fulfilled in our case for an IPEA 550.

d) Comparative approach

By using a deterministic or probabilistic approach we have to prove that an alternative profile could fulfil the criterion at least as safe as a HEA 400 (see prescriptive approach a).

Using for example a deterministic approach:
IPEA 600 S235 (M_{pl} = 737 kNm) > HEA 400 S235 (M_{pl} = 602 kNm)
IPEA 500 S355 (M_{pl} = 692 kNm) > HEA 400 S235 (M_{pl} = 602 kNm)

A comparative approach will lead to more conservative results than the basic (prescriptive) solution. But by using alternative profiles a saving in steel is still possible (IPE A 600 S235 (108 kg/m') < HEA 400 (125 kg/m')).

e) Systems approach

From example C we can see that the mean value of q is only 16 kN/m. By using a strain measure and alarm device not allowing more people in the room than resulting in an accepted stress level in the beam a smaller profile could be allowed than a IPE A 550. The accepted failure probability could be found by:

$$p_{f,acc} = p_{f,acc,sys} \cdot p_{measuring}$$

e.g. for an accepted structural failure probability of $7{,}25 \cdot 10^{-5}$ per working life of the building and an availability of monitoring device of 95%.

$$p_{f,fi,acc} = 7{,}25 \cdot 10^{-5} / (1 - 0{,}95) = 1{,}45 \cdot 10^{-3} = 0{,}00145$$

A FORM analysis like in example c) shows that an IPE A 500 S235 will fulfil this acceptance criterion.

Probabilistic design resistance

	nominal	fractile	m	σ	V	Law
P	20	50%	20	2	0,1	N
N	25	95%	16	4,8	0,3	GL
R	235	95%	255,987	13,3	0,052	LN

The limit state function is defined as followed:

$$G = R_{pl} - \left(\frac{(N+P) \cdot l^2}{8}\right) = f_y \cdot Z - \left(\frac{(N+P) \cdot l^2}{8}\right) = (f_y \cdot Z)/1000 - ((N+P) \cdot L\text{^}2)/8$$

Variables of G:

L	D	8,000	
W	D	1,950e+03	
N	GL	13,840	0,267
P	N	20,000	2,000
f_y	LN	5,544	0,052

FORM Analysis of G:

IPE A 500 β = HL - Index = 3,16 $p(G<0) = 0{,}000787 = 7{,}87 \cdot 10^{-4}$

$p(G<0) = 7{,}87 \cdot 10^{-4} < p_{f,fi,acc} = 1{,}45 \cdot 10^{-3}$.

The profile IPE A 500 S235 together with a monitoring device fulfils the acceptance criterion.

Note: The serviceability $\delta(q) < \ell/300$ is here not considered.

ANNEX C

1 INTRODUCTION

1.1 ABSTRACT

This case study describes three methods to quantify the influence of natural fire conditions and active fire protection measures on the structural fire resistance design. For an existing office building the safety levels of two building concepts (e.g. one according to the prescriptive fire regulations and an alternative design) are analysed and compared. For this comparison the following three risk based methods are applied:

- The "Risk Evaluation" method according to **SIA DOC 81** (Gretener Method [21]) is an easy to apply grading method for a rapid risk assessment.
- The **probabilistic NFSC-Method** applies natural fires for a performance based structural fire design. The quantification of active measures on the structural reliability is based on a probabilistic approach.
- The **simplified NFSC-Method** [28] uses the same probabilistic background to fix partial safety factors γ, which can then be used in a deterministic analysis.

1.2 SCOPE AND AIM OF THE PROBABILISTIC NFSC METHOD

The NFSC-Method gives a framework to analyse in a **comparative way** alternative, not code complying concepts with the prescriptive requirements of the national fire regulations with regard to the fire resistance.

The method does not fix an absolute level of acceptable risk but uses a comparative procedure in which it is assumed that the national fire regulations represent an acceptable safety level.

For active fire protection measures the described method quantifies only the influence on the structural fire resistance design. Further benefits of active measures with regard to life safety (e.g. from egress, smoke) are not yet taken into considerations.

Even by neglecting these important benefits the new flexibility gained by designing for fire safety with such methods, especially for industrial or public buildings, makes it possible to recognise the interaction between structural fire protection and active fire safety measures. It can lead to considerable savings especially for steel and composite structures without reducing the fire safety level.

Note: The following case study "Langenthal" is a first attempt to apply the NFSC-Method and to compare it to other methods. The example does not aim to be a final proposal of the method. Further research and discussions regarding for e.g. the amount of fire load, the breaking of windows, acceptance criteria and other parameters is needed in the future.

1.3 SUMMARY

This summary gives a short overview of the content of the case study for hurried readers.

1. INTRODUCTION

Aim, scope and limitations of the described method are mentioned.

2. DESCRIPTION OF THE BUILDING

The architectural design of the existing office building is reviewed providing the building layout, the combustible material, the ventilation conditions and information about the occupancy and the design loads.

3. DESIGN OF REFERENCE SECTIONS AT ROOM TEMPERATURES

For the code complying and for the alternative fire safety design (which has actually been built) the structural system and the section design are reviewed. The deterministic resistance and the failure probability are calculated for cold design.

4. DESIGN OF REFERENCE SECTIONS IN CASE OF FIRE

For the code complying and for an alternative fire safety design the structural system and the section design is reviewed. The deterministic resistance and the failure probability are calculated for fire design.

5. DESCRIPTION OF THE PROBABILISTIC NATURAL FIRE SAFETY CONCEPT

The modelling of the actions and the structural response of a building in a natural fire according the NFSC-Method is explained. The probabilistic method is described showing the procedure, assumptions and background.

6. APPLICATION OF THE PROBABILISTIC NATURAL FIRE SAFETY CONCEPT

The NFSC-Method is applied on the code complying and the alternative building design.

7. SWISS RISK EVALUATION METHOD

It is a grading method based on a large statistical survey. The procedure consists in the verification of a value of a global fire safety factor γ. It is applied to the code conforming and the alternative design.

8. SIMPLIFIED NATURAL FIRE SAFETY CONCEPT

The simplified NFSC method uses partial safety factors γ to analyse the risk levels of the two alternative building concepts. The partial safety factors cover the compartment area, the danger of activation and the benefits of the use of active fire fighting measures.

9. COMPARISON AND CONCLUSION

The results found by applying of the three methods are discussed.

2 DESCRIPTION OF THE BUILDING

2.1 DESCRIPTION OF THE BUILDING

The following example is a four storey steel-framed office block in Langenthal in the canton of Berne realised in 1992 [20]. The office building was built for the municipal and district administration.

It is an office block for 200 employees with a total volume of 33.000 m^3. The ground floor area, the two basement floors and the upper three floors include 1.306 m^2 each. The building has a length of 80 m, a width of 20 m and a height of 16 m.

The basement of the building is realised in reinforced concrete and the ground floor up to the 3rd storey by a structural steel frame with pre-stressed concrete slab elements. The round steel columns are located on the outside of the office area and the facade so that an optimal room compartmentation can be achieved.

The office building has no air-conditioning system, the temperature can be regulated by opening and closing the windows.

The fire safety concept includes three smoke resistant fire compartments (each storey with a size of 80 . 20 = 1.600 m^2). One is designed as central open staircase with direct access to a limited number of office rooms. The escape routes are not code-conform but agreed with the Cantonal fire authority (GVB/AIB) and include three glazed escape staircases with an E30 rating (smoke and flame-proof glass, with no resistance against radiation).

Basic normal measures are portable fire extinguisher and indoor hydrants. As a monitoring concept a smoke detection system is installed in the entire building with a first alarm to reception desk located in the building itself. The local public fire brigade (top category class) is located in the immediate vicinity of the building. Besides all this the lightning protection device is sufficient.

The structural fire resistance for the two basement storeys is R60. The steel columns at the outside as well as the inner solid or composite steel columns are not protected and are rated R30. The inner steel beams are protected with an intumescent paint to reach R30.

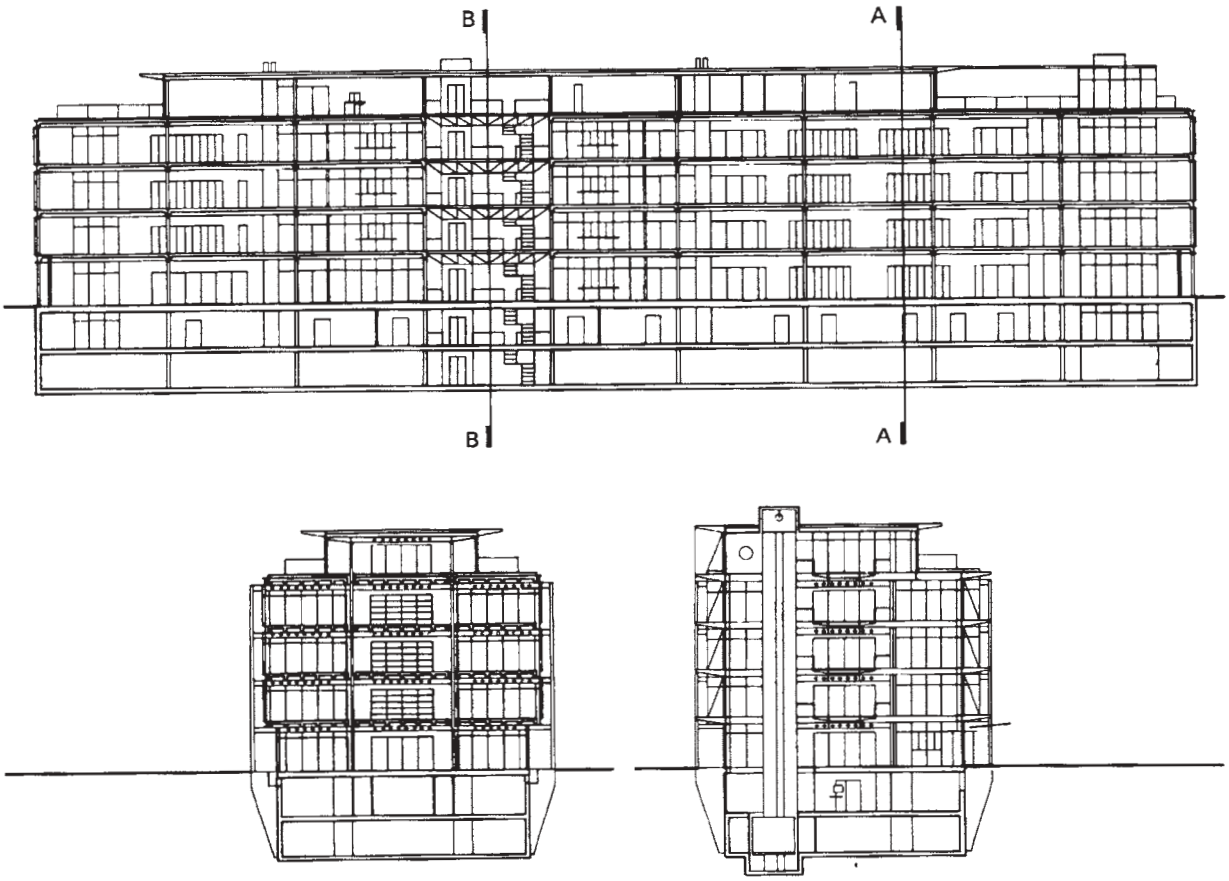
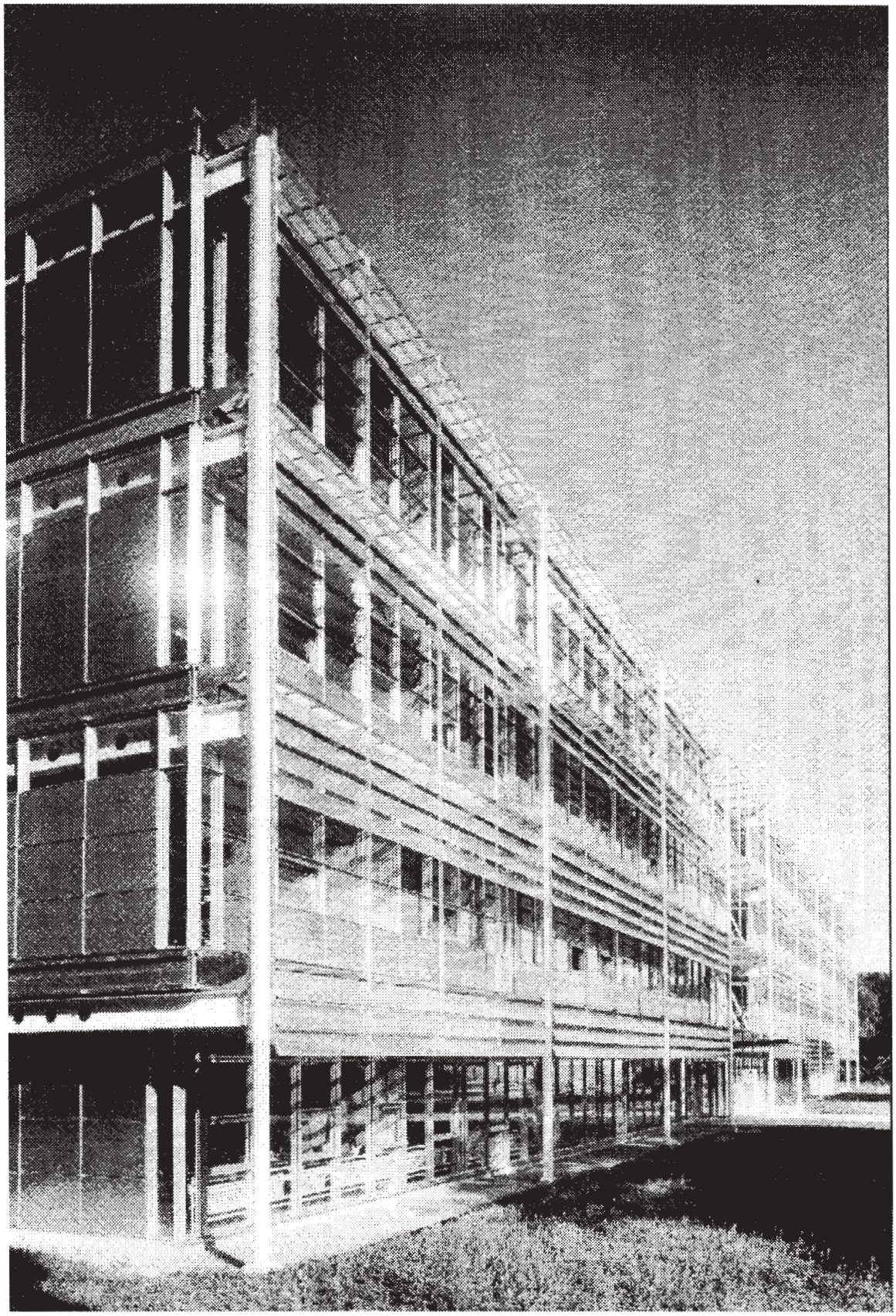


Figure C1: Four storeys steel frame office building



Picture 1: Office building Langenthal

2.2 STRUCTURAL SYSTEM AND LOADS

The structure consists of a braced steel frame with continuous 6,66 m span steel beams (IPE 400) and 3,20 m long continuous steel columns (ROR ⌀ 298,5 mm, t = 20 mm[1]) with the following loads:

Self weight:

Steel beam IPE 400 $g = 0{,}66$ kN/m

Concrete slab element $g = 2{,}5$ kN/m^2
(d = 10 cm)

60 mm cement coating $g = 1{,}2$ kN/m^2

15 mm surface coating $g = 0{,}3$ kN/m^2

$g_{tot} = 4{,}66$ kN/m^2

$b = 8{,}88$ m

$G_B = 41{,}4$ kN/m

Steel column ROR ⌀ 298,5 $g = 1{,}37$ kN/m
(t = 20 mm)

$g_{tot} = 1{,}37$ kN/m^2

$\ell = 3{,}20$ m

$G_C = 4{,}3$ kN

Imposed load: Office building (code of action SIA 160 [30]: category B)

$q_{general} = 3{,}0$ kN/m^2

$b = 8{,}88$ m

$N_B = 26{,}6$ kN/m

Snow load $h = 476$ m

$$s = \left[1 + \left(\frac{476}{350}\right)^2\right] \cdot 0{,}4\,\text{kN/m}^2 = 1{,}14\,\text{kN/m}^2$$

$$S = \xi \cdot s = 0{,}8 \cdot 1{,}14\,\text{kN/m}^2 = 0{,}91\,\text{kN/m}^2$$

2.3 ROOM CHARACTERISTICS

For the case study two room geometry's have been analysed and will be compared:

- The first corresponds to the **code design**, which would have been built according the national prescriptive regulations [22] (see Figure C2).
- The alternative and **existing design** which has actually been built in Langenthal represents an attempt to reach the same risk level as by the code design but with less structural measures and considering active fire fighting measures (see Figure C3)

[1] Note: In the existing building solid columns Ø 177.8 mm are used. These columns reach a fire resistance of about 45 minutes i.e. more than the required 30 minutes. Therefore in the example ROR Ø 298.5 mm, t = 20 mm sections were used having a fire resistance of about 30 minutes as required.

2.3.1 CODE DESIGN

The code design [22] allows 600 m^2 maximum office space without active measures and requires a resistance R60 of the structural elements. Therefore the design office room was taken as part of the storey (fire compartment size of 20 m · 30 m) with windows on three sides.

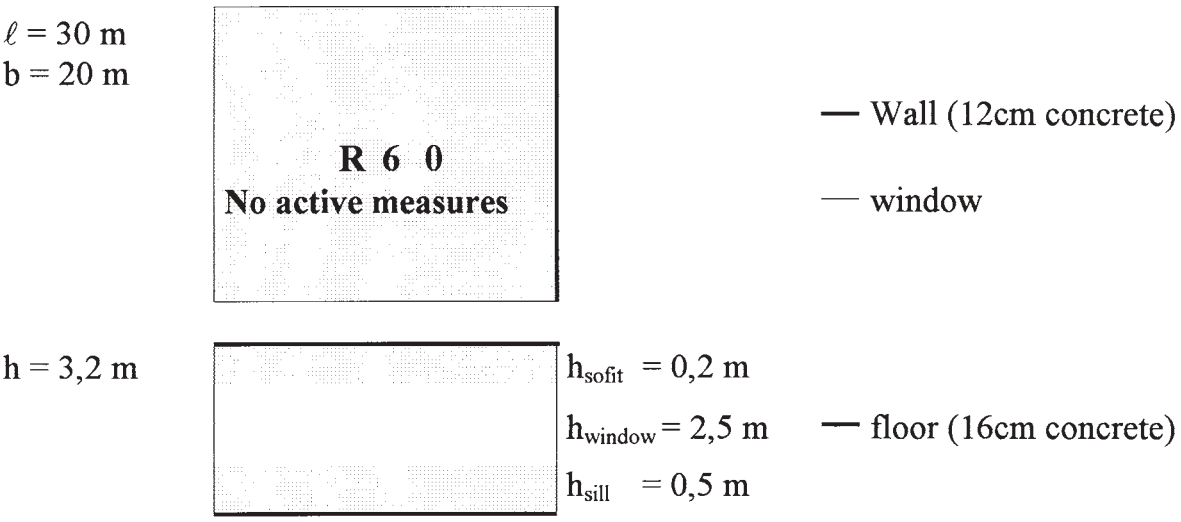


Figure C2: Room and ventilation characteristics for small office (20m · 30m)

2.3.2 EXISTING DESIGN

The existing design has no compartmentation and a fire resistance R30 of the structure. Therefore the design office was taken as the whole storey (fire compartment size of 20 m / 80 m) with windows on four sides.

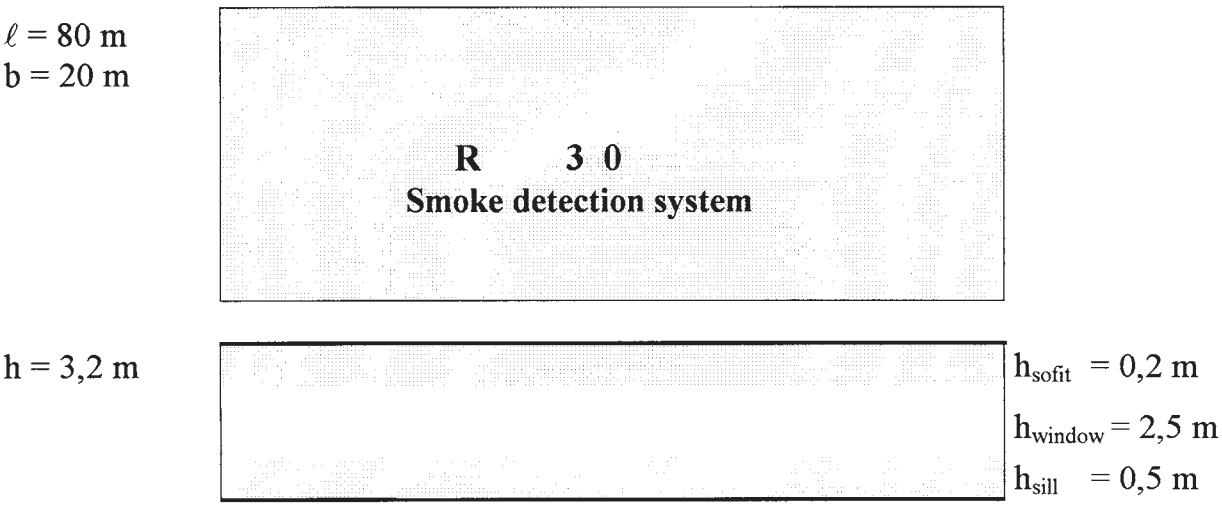


Figure C3: Room and ventilation characteristics for large office (20m · 80m)

These room characteristics were used as input data for the parametric design fire studies with the BSBG one zone fire simulation program [26] (see chapter 6.3.4).

3 DESIGN OF REFERENCE SECTIONS FOR ROOM TEMPERATURE

3.1 STEEL BEAM

3.1.1 STRUCTURAL SYSTEM AND LOADS

Continuous steel beam with 6,66 m span and the following loads

Beam: Self weight: $G_B = 41{,}4$ kN/m
Imposed load: $N_B = 26{,}6$ kN/m

3.1.2 LOAD LEVEL FOR COLD DESIGN

The design load at room temperature is calculated with partial safety factors given in design codes e.g. Eurocodes [6] 9.2 and [8]:

$q_d = \gamma_g \cdot G_B + \gamma_Q \cdot N_B$
$q_d = 1{,}3 \cdot G_B + 1{,}5 \cdot N_B = 1{,}3 \cdot 41{,}4$ kN/m $+ 1{,}5 \cdot 26{,}6$ kN/m $= 93{,}7$ kN/m

For a continuous beam with three spans the plastic moment can be calculated as:

$$M_d = {}^{1}\!/_{11{,}67} \cdot q_d \cdot l^2 = {}^{1}\!/_{11{,}67} \cdot 93{,}7 \cdot 6{,}66^2 = 356{,}1 \text{ kNm}$$

3.1.3 DETERMINISTIC DESIGN RESISTANCE FOR ROOM TEMPERATURE

The beam dimensions are chosen as followed:
IPE 400 (S355) with $A = 8450$ mm^2
$I_y = 231{,}3 \cdot 10^6$ mm^4
$Z_y = 1.310 \cdot 10^3$ mm^3
$f_y = 355$ N/mm^2

$$M_R = f_y \cdot Z_y = 355\,{}^{N}\!/_{mm^2} \cdot 1310 \cdot 10^3\,mm^3 = 465{,}1 \text{ kNm}$$

$S_d \le R_d = M_R / \gamma_R$
$356{,}1$ kNm $\le 465{,}1$ kNm $/ 1{,}1 = 422{,}8$ kNm

$\eta = S_d / R_d = 356{,}1$ kNm $/ 422{,}8$ kNm $= 0{,}84$

The IPE 400 beam fulfils the requirement at room temperature. The deflection is here not considered.

3.1.4 PROBABILISTIC DESIGN FOR ROOM TEMPERATURE

To demonstrate the probabilistic design approach the reliability of the beam which was designed in a traditional deterministic way (see 3.1.3) is calculated hereafter. The term reliability is here defined as the probabilistic measure of assurance of performance [2]. We calculate the probability of failure $p_f = P\,[G(X) \le 0]$ using the FORM (First Order Reliability Method) procedures [12].

3.1.5 LIMIT STATE FUNCTION G FOR ROOM TEMPERATURES

The limit state function is defined as followed: [17]

$$G = R_{pl} - \left(\frac{(N_B + G_B) \cdot l^2}{11{,}67} \right) = f_y \cdot Z - \left(\frac{(N_B + G_B) \cdot l^2}{11{,}67} \right) = (f_y*Z)/1000-((N_B+G_B)*L\text{^}2)/11{,}67$$

3.1.6 PROBABILITY DENSITY FUNCTION (PDF) FOR EACH VARIABLE (COLD)

Self weight:

G_B: law: Gaussian

nominal value : 50% fractile = 41,4 kN/m [6] chapter 4.2

$V_G = 0{,}1$ [4] chapter 9.3.1

$m_G = 41{,}4$ kN/m

$\sigma_G = m_G \cdot V_G = 4{,}14$ kN/m

Variable load:

N_B: law: Gumbel Type I [4] chapter 9.3.1

nominal value : 5% fractile = 26,6 kN/m [6] chapter 4.2

$V_N = 0{,}3$ [4] chapter 9.3.1

$m_N = 26{,}6$ kN / 1,56 = 17,1 kN/m

$\sigma_N = m_N \cdot V_N = 5{,}13$ kN/m

Structural steel:

f_y: law: lognormal

nominal value : 95% fractile = 355 N/mm^2

$V_R = 0{,}052$ [5] (Table 2.3)

$m_R = e^{1{,}645 V_R} \cdot 355$ N/mm^2 = 386,7 N/mm^2 [5] (2.5)

$\sigma_R = m_R \cdot V_R = 20{,}11$ N/mm^2

	nominal	fractile	m	σ	V	Law
G_B	41,4	50%	41,4	4,14	0,1	N
N_B	26,6	95%	17,1	5,13	0,3	GL
f_y	355	5%	386,7	20,11	0,052	LN

3.1.7 PROBABILISTIC DESIGN RESISTANCE

The FORM Analysis of G with the program VaP [3] showed a safety index of $\beta = 5{,}43$ ($p_f = 2{,}84 \cdot 10^{-8}$) for the steel beam IPE 400 (S355). For a comparison a Monte Carlo Analysis of G was performed with 10'000'000 samples where for the beam no failure was found.

3.2 STEEL COLUMN

3.2.1 STRUCTURAL SYSTEM AND LOADS

The characteristic load values according to chapter 2.2 are used to evaluate the design loads.

Ground floor: Room height: h = 2,96 m
Buckling length: ℓ_{cold}= 2,96 m

Imposed load: $G_{B,tot} = \ell \cdot G_B$ = 6,66 m · 41,4 kN/m = 275,7 kN
$N_C = \ell \cdot N_B$ = 6,66 m · 26,6 kN/m = 177,2 kN

Snow load: S = $0.91\,kN/m^2 \cdot 6.94m \cdot 8.88m$ = 56,0 kN

Self weight: Steel column ROR ⌀ 298,5, t = 20 mm
G_C= 3,2 m · 1,37 kN/m = 4,3 kN

3.2.2 LOAD LEVEL FOR COLD DESIGN

The design load at room temperature for each floor (ground floor, 1st, 2nd and 3rd floor) is:

$S_{d,storey}$ = 1,3 · (G_C + N_C)+1,5 · $G_{B,tot}$ = 1,3 · (4,3 kN + 177,2 kN)+ 1,5 · 275,7 kN
= 649,5 kN

And for the column of the ground floor:

S_d = 1,3 · (5 · G_C + 4 · N_C) + 1,5 · (4 · $G_{B,tot}$) + 0,8 · S
= 1,3 · (5 · 4,3 kN + 4 · 177,2 kN) + 1,5 · (4 · 275,7 kN) + 0,8 · 56,0 kN = 2648,4 kN

3.2.3 DETERMINISTIC DESIGN RESISTANCE FOR ROOM TEMPERATURE

Deterministic design resistance for room temperature

ROR ⌀ 298,5 mm (t = 20mm)
A = 17500 mm²
A_m/V = 1/t = 50 m^{-1}
I = 170,5 · 10^6 mm^4
i = 98,7 mm
ℓ = 2,96 m
f_y = 235 N/mm²

$$R_{d,20°C} = \kappa_{c,20°C} \cdot A \cdot f_y = 0{,}9393 \cdot 17500 \cdot 0{,}235 = 3862{,}9\ kN$$

with $$\kappa_{c,20°C} = \frac{1}{\varphi + \sqrt{\varphi^2 - \bar{\lambda}_{20°C}^{\,2}}} = 0{,}9393$$

α_c = 0,49

$$\varphi = 0{,}5 \cdot \left[1 + \alpha \cdot \left(\bar{\lambda}_{20°C} - 0{,}2\right) + \bar{\lambda}_{20°C}^{\,2}\right] = 0{,}5802$$

$$\bar{\lambda}_{20°C} = \frac{l_{k,cold}}{\sqrt{I/A} \cdot \pi \cdot \sqrt{E/f_y}} = \frac{2960}{98{,}7 \cdot \pi \cdot \sqrt{210000/235}} = 0{,}3193$$

S_d ≤ R_d / γ_R
2648,4 kN ≤ 3862,9 kN / 1,1 = 3511,7 kN
$\eta = S_d / R_d$ = 2648,4 kN / 3511,7 kN = 0,754
The column ROR ⌀ 298,5 mm (t = 20mm) fulfils the requirement at room temperature.

3.2.4 PROBABILISTIC DESIGN FOR ROOM TEMPERATURES

The limit state function G becomes:

$G = R_{pl} - (N_C + G_C)$

$=((1/((0,5*(1+0,49*((l_k/((I/A)^0,5)/(\pi*((E/f_y)^0,5)))-0,2)+(l_k/((I/A)^0,5)/(\pi*((E/f_y)^0,5)))^2))+((0,5*(1+0,49*((l_k/((I/A)^0,5)/(\pi*((E/f_y)^0,5)))-0,2)+(l_k/((I/A)^0,5)/(\pi*((E/f_y)^0,5)))^2))^2-(l_k/((I/A)^0,5)/(\pi*((E/f_y)^0,5)))^2)^0,5))*A*f_y/1000)-(N_C + G_C)$

3.2.5 PROBABILITY DENSITY FUNCTION (PDF) FOR EACH VARIABLE (COLD)

Self weight:

G_C: law: Gaussian

nominal value : 50% fractile = $5 \cdot G_C + 4 \cdot G_{B,tot}$ [6] chapter 4,2

= 16,1 m · 1,37 kN/m + (4 · 275,7 kN) = 1124,9 kN

$V_Q = 0,1$ [4] chapter 9,3,1

$m_Q = 1124,9$ kN

$\sigma_Q = m_Q * V_Q = 112,49$ kN

Variable load:

N_C: law: Gumbel Type I [4] chapter 9.3.1

nominal value : 95% fractile = $4 \cdot N_C + S$ [6] chapter 4.2

= (4 · 177,2 kN) + 56 kN = 764,8 kN

$V_N = 0,3$ [4] chapter 9.3.1

$m_N = 764,8$ kN/1,56 = 490,3 kN

$\sigma_N = m_N * V_N = 147,1$ kN

Structural steel:

f_y: law: lognormal

nominal value : 5% fractile = 235 N/mm^2

$V_R = 0,052$ [5] (Table 2.3)

$m_R = e^{1,645 V_R} * 235$ N/mm^2 = 255,987 [5] (2.5)

$\sigma_R = m_R * V_R = 13,3$

	nominal	fractile	m	σ	V	Law
G_C	1124,9	50%	1124,9	112,49	0,1	N
N_C	764,8	95%	490,3	147,1	0,3	GL
f_y	235	5%	255,987	13,3	0,052	LN

3.2.6 PROBABILISTIC DESIGN RESISTANCE

The FORM Analysis of G with the program VaP [3] achieves no iteration accuracy for the steel column ROR ∅ 298,5 mm (t = 20mm) because we are on the very safe side ($\beta > 5$). For a comparison a Monte Carlo Analysis of G was performed with 10.000.000 samples where for the beam no failure was found.

4 DESIGN OF REFERENCE SECTIONS IN CASE OF FIRE

4.1 ACTIONS IN CASE OF FIRE

For the structural response in case of fire two groups of actions have to be taken in account:

- Mechanical actions (loads present at the time of fire, restraints resulting from thermal elongation and deformation)
- Thermal actions (steel temperature resulting from the fire)

4.1.1 MECHANICAL ACTIONS

Fire is a rare event with the thermal action as main action, therefore in a deterministic design approach the (accompanying) mechanical actions (loads) can be taken as a more frequent fractile than if it is the main action in cold design. This is done by using a factor ψ smaller than γ_Q (e.g. 0,5 instead of 1,5) (see [6] and [8]).

4.1.1.1 Steel beam

According to Eurocode 1 part 2-2 [8] the design load in case of fire for offices is (see chapter 3.1.2):

$$q_{d,fire} = \gamma_{g,fire} \cdot G_B + \psi \cdot N_B = 1,0 \cdot G_B + 0,5 \cdot N_B = 1,0 \cdot 41,4 kN/m + 0,5 \cdot 26,6 kN/m = 54,7 \text{ kN/m}$$

$$M_{d,fire} = \frac{q_{d,fire} \cdot l^2}{11,67} = \frac{54,7 \cdot 6,66^2}{11,67} = 207,9 \text{ kNm}$$

4.1.1.2 Steel column

Continuous column: Room height: h = 2,96 m
Buckling length: ℓ_{fire}= 1,5 m

The design load at room temperature for each floor (ground floor, 1st, 2nd and 3rd floor) is calculated according chapter 3.2.2:

$$S_{d,storey} = 1,0 \cdot (G_C + N_C) + 0,5 \cdot G_{B,tot} = 1,0 \cdot (4,3 \text{ kN} + 177,2 \text{ kN}) + 0,5 \cdot 275,7 \text{ kN} = 319,4 \text{ kN}$$

And for the column of the ground floor:

$$S_d = 1,0 \cdot (5 \cdot G_C + 4 \cdot N_C) + 0,5 \cdot (4 \cdot G_{B,tot})$$
$$= 1,0 \cdot (5 \cdot 4,3 \text{ kN} + 4 \cdot 177,2 \text{ kN}) + 0,5 \cdot (4 \cdot 275,7 \text{ kN}) = 1281,7 \text{ kN}$$

4.1.2 THERMAL ACTIONS

The thermal action is the main action for the structure in case of fire. The requirements for the code (R60) and the alternative design (R30) are based on the ISO-fire-curve: This allows an easy design using e.g. the nomogram ECCS N° 89 [1].

4.2 DESIGN OF FIRE PROTECTION R60 AND R30

4.2.1 DETERMINISTIC DESIGN OF FIRE PROTECTION FOR THE BEAM

With the design moment for the fire situation (see chapter 4.1.1.1) and the plastic moment in case of fire at the time zero (i.e. the same as in cold design see chapter 3.1.3) for the IPE 400 S235 the degree of utilisation in fire is calculated to:

$\mu_0 = M_{d,fire} / M_{R,fire,t=0} = 207{,}9 \text{ kNm} / 465{,}1 \text{ kNm} = 0{,}447$

From the Nomogram ECCS N° 89 [1] for $\mu_0 = 0{,}447$ and $\kappa = 0{,}85$ a critical temperature of $\theta_{crit} = 627{,}7$ °C can be calculated [9] and the unprotected beam IPE 400 with $A_m / V = 174$ resists 14,7 min in the fire case.

The inner steel beams are protected with an intumescent paint. The case of insulation with an intumescent paint can not be calculated with the Nomogram or with the design formulas from EC3 part 1-2 [9]. As an alternative solution the paint is replaced in this example by a sprayed material. The material properties of that fire protection material are chosen as followed:

$c_p = 1200 \quad J/kg \cdot K$

$\rho_p = 350 \quad kg/m^3$

$\lambda_p = 0{,}12 \quad W/mK$

$A_p/V = 174$ (fired on four sides)

$$4000 = \frac{A_p/V}{\lambda_p/d_p} = \frac{174}{0{,}12/d_p}$$

$$d_p = \frac{174 \cdot 0{,}12}{4000} = 0{,}0052 \text{ m} \approx 5 \text{ mm}$$

To reach a fire resistance of 30 minutes a modified section factor of (A_p/V) $(\lambda_p/d_p) \approx 4000$ or 5 mm insulation and to reach 60 minutes 12 mm of insulation is needed.

Steel section	Insulation painting	κ	μ_o	θ_{crit} [°C]	d_p [mm]	$(A_p/V) \cdot (\lambda_p/d_p)$ [W/(m³ · K)]	t_{crit} [min]	R_{fire}
IPE 400	Perlit	0,85	0,447	627,7	4	5220	29,2	R15
IPE 400	**Perlit**	**0,85**	**0,447**	**627,7**	**5**	**4176**	**34,1**	**R30**
IPE 400	Perlit	0,85	0,447	602,5	11	1898	59,7	R45
IPE 400	**Perlit**	**0,85**	**0,447**	**602,5**	**12**	**1740**	**63,9**	**R60**

Table C1: Parameter study for the insulated steel beam

4.2.2 DETERMINISTIC DESIGN RESISTANCE OF FIRE PROTECTION FOR THE COLUMN

In this design example the steel column R30 were chosen as ROR ⌀ 298,5 mm, t = 20mm (see note on page 152).

The calculation of the fire resistance of a column needs an iterative procedure starting from the resistance $R_{d,20°C}$ at room temperature and the buckling length in case of fire $\ell_{fire} = 0{,}5 \cdot \ell_0 = 1{,}48$m [9]:

With Table 1b from the Nomogram [1] the iterative procedure can be avoided. With $\bar{\lambda}_{0,c} = 0{,}3193$ and $\mu_{0,c} = 0{,}3318$ a critical temperature of $\theta_{cr} = 630$ °C can be found in Table 1b of [1].

ROR ⌀ 298,5 mm (t = 20mm)

$A = 17500$ mm²
$A_m/V = 1/t = 50$ m^{-1}
$I = 170{,}5 \cdot 10^6$ mm⁴
$i = 98{,}7$ mm
$\ell_{cold} = 2{,}96$ m
$\ell_{fire} = 1{,}48$ m
$f_y = 235$ N/mm²

$R_{d,20°C} = \kappa_{0,c} \cdot A \cdot f_y = 0{,}9393 \cdot 17500 \cdot 0{,}235 = 3862{,}9$ kN

with $\kappa_{0,c} = \dfrac{1}{\varphi + \sqrt{\varphi^2 - \bar{\lambda}_{0,c}^2}} = 0{,}9393 \le 1{,}0$

$\alpha_c = 0{,}49$

$\varphi = 0{,}5 \cdot \left[1 + \alpha \cdot \left(\bar{\lambda}_{0,c} - 0{,}2\right) + \bar{\lambda}_{0,c}^2\right] = 0{,}5802$

$\bar{\lambda}_{0,c} = \dfrac{l_{k,cold}}{\sqrt{I/A} \cdot \pi \cdot \sqrt{E/f_y}} = \dfrac{2960}{98{,}7 \cdot \pi \cdot \sqrt{210000/235}} = 0{,}3193$

Load level $\mu_{0,c} = N_{fi,d} / R_{d,20°C} = 1281{,}7$ kN / 3862,9 kN = 0,3318 (see chapter 4.1.1.2)

From the Nomogram [1] with $\theta_{cr} = 630$ °C and a column **ROR ⌀ 298,5 mm (t = 20mm)** ($A_m/V = 1/t = 50$ m^{-1}) a fire resistance of 29,8 minutes is found (R30).

With the same procedure and a column **⌀ 190,0 mm** ($A_m/V = 21{,}1$ m^{-1}) (S355 with $f_y = 295$ N/mm², the yield strength has to be reduced for at thickness of the steel) with $\mu_{0,c} = 0{,}2197$ and $\kappa = 1{,}2$, a critical temperature of $\theta_{cr} = 713{,}8$ °C is calculated and the column would resist 61,1 minutes.

5 DESCRIPTION OF THE NATURAL FIRE SAFETY CONCEPT

5.1 GENERAL

The natural fire safety concept (NFSC-Method) aims at modelling the actions and the structural response in case of a building fire in a realistic way. The thermal action and the structural response are calculated on the basis of physical models. However the main input parameters are taken as variables. Further the occurrence of fire and the probability of a fire to grow into a severe fire are taken into account when calculation the reliability of the structure in case of fire.

The method comprises the following subsystem analysis

- fire occurrence and fire growth
  - probability of fire occurrence and fire growth
  - influence of active measures like sprinkler systems, fire brigade etc.

- structural response
  - thermal actions
  - mechanical actions
  - structural behaviour (fire resistance)

The synthesis of the two subsystems e.g. the quantification of the performance of the structure in case of fire is done on the basis of the reliability index β per period of time (per year or life time). The reliability index is in our case a measure of the probability of not having a structural failure due to fire during that period.

The NFSC-Method considers both subsystems: the probability of having a severe fire (taking into account the benefit of the fire brigade and active measures) and the reliability of the structure in case of a severe fire taking into account real fire conditions (fire load, ventilation conditions...) and fire resistance (fire protection, global structural behaviour...).

5.2 FIRE OCCURRENCE AND FIRE GROWTH

5.2.1 EVENTS LEADING TO A SEVERE FIRE

A typical event tree is shown in Figure C4. It describes the steps in the fire growth until structural damage occurs:

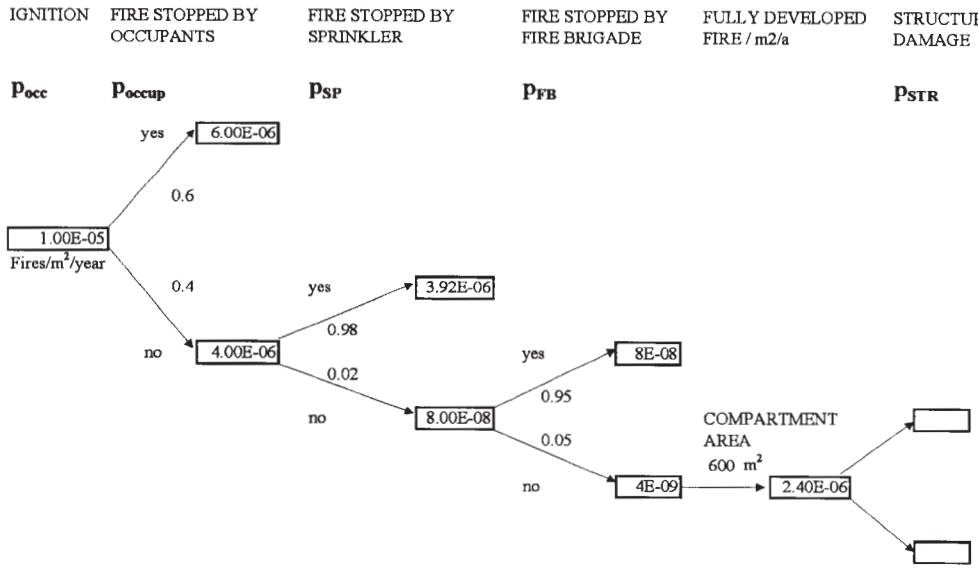


Figure C4: Example for an event tree for fire growth leading to a severe fire and structural collapse (office with a compartment area of 600 m^2). Note: the numbers are given only as an example.

Each event leading to a severe fire is characterised by a probability of occurrence. This input data can be based on statistics, submodel calculation or engineering judgement.

5.2.2 FREQUENCY OF OCCURRENCE OF A SEVERE FIRE

As only severe fires are able to endanger a structure the event tree can be summarised to: $p_{severe,fire} = p_1 \cdot A^x \cdot n \cdot p_M$ (1)

- p_1 : probability of fire occurrence for a certain occupancy per year and m^2
- A : Room area
- x : Exponent $x \leq 1{,}0$ taking into account the compartment size
- n : building lifetime (50 years)
- p_M : failure probability of fire fighting measures

Note: p_M can be split into the different events according to Figure C4.

5.2.3 STATISTICAL BACKGROUND ON FIRE OCCURRENCE AND FIRE GROWTH

On the basis of nearly 40.000 fires in Berne from 1986 to 1995 [13] the frequency of fire occurrence and fire growth was deduced in function of the size of loss to the building structure reported and the floor area. Table 1 shows the frequency of fire occurrence and growth to a given loss size. For example the frequency of fire starts in industrial building was found as $11{,}6 \cdot 10^{-6}$ / m^2 · year and the frequency of fires to start and to grow as large as to cause a loss to the building structure of more than 99.999 CHF is $0{,}85 \cdot 10^{-6}$ / m^2 · year. The decrease of the fire occurrence frequency with increasing compartmentation or building size could not be studied on the basis of the available data, the frequencies are therefore average values over the whole building group of Berne.

Loss-size	All [10^{-6}] / m^2 · year	Dwellings [10^{-6}] / m^2 · year	Office / Public [10^{-6}] / m^2 · year	Industrial [10^{-6}] / m^2 · year
All losses	32,3	33,3	10,60	11,6
>1.999	9,18	9,22	4,35	6,48
>49.999	0,927	0,710	0,40	1,32
>99.999	0,641	0,460	0,27	0,85

Table C2: Frequency of fire occurrence and growth to a given loss size [per m^2 · year] for different occupancy classes

If one would judge that fires causing a loss < 2.000 CHF are self terminated or stopped by the occupants [14] and fires causing a loss < 50.000 CHF (or < 1.000.000 CHF in industrial buildings) were successfully handled by the fire brigade partial factors for p_M can be established. The resulting probability of fire start and growth to severe fire with public fire brigade present is shown in Table C3.

Occupancy	p_1 [$10^{-6}/m^2$ ·year]	Exponent x
Office	0,2 - 0,4	0,75 - 1,0
Dwelling	0,4 - 0,9	1,0
Industrial	0,5 - 1,0	0,3 - 1,0

Table C3: Probability of fire start and growth to severe fire with public fire brigade present

Detailed values for different fire fighting measures (e.g. sprinkler systems, smoke detectors...) are compared and recommended in [14, 24 and 25].

5.2.4 STRUCTURAL FAILURE PROBABILITY IN CASE OF FIRE

A structure can only fail in fire if there is a severe fire. From this trivial statement we can distinguish two structural failure probabilities:

- p_f : structural failure probability from a fire free status (unconditional failure probability)
- $p_{f,fi}$: structural failure probability given a severe fire (conditional failure probability)

The relation between the conditional and the unconditional failure probability is given by:

$$p_f = p_{severe,fire} \cdot p_{f,fi}$$

$p_{severe,fire}$: probability to have a severe fire (see chapter 5.2.2)
$p_{f,fi}$: conditional failure probability for structural failure (can be calculated by the method given in chapter 5.6).

5.3 ACTIONS IN CASE OF FIRE

For the structural response in case of fire two groups of actions have to be taken in account:

- Mechanical actions (loads present at the time of fire restraints resulting from thermal elongation and deformation)
- Thermal actions (steel temperature resulting from the fire)

5.3.1 MECHANICAL ACTIONS

Fire is a rare event with the thermal action as main action, therefore in a deterministic design approach the (accompanying) mechanical actions (loads) can be taken as a more frequent fractile than in cold design (see chapter 4.1.1).

In a purely probabilistic approach (e.g. FORM analysis) the mechanical actions are taken as variables (with distribution type, μ, σ, V) and no ψ or γ_Q factors are needed.

5.3.2 THERMAL ACTIONS

The thermal action is the main action for the structure in case of fire. The main parameters influencing the time temperature curve are:

- the fire load (fire load density, rate of heat release)
- the ventilation conditions
- the thermal characteristics of the enclosure
- fire fighting measures

There are three methods of modelling the thermal actions

- Nominal time-temperature curves (e.g. ISO-fire-curve [8], carbon-fire-curve...). The main parameters can only be taken into account by the fire duration and by choosing the appropriate curve thus leading to a rough and in some cases unrealistic description of the thermal actions.
- Parametrical fire formulas taking into account some parameters in a analytical formula (e.g. Annex B of EC1 part 2-2 [8] for ventilation controlled fires)
- Computer aided fire simulations based on zone or CFD-models.

5.3.3 FIRE LOAD

The fire load per m^2 floor area can be found by measurement in the building or on the basis of statistical data. Table 4 from [7] gives data on the fire load distribution for different occupancies:

	mean [MJ/m²]	80% [MJ/m²]	90% [MJ/m²]	95% [MJ/m²]
Dwelling	780	870	920	970
Hospital	230	350	440	520
Hospital storage	2000	3000	3700	4400
Hotel bedroom	310	400	460	510
Offices	**420**	**570**	670	760
Shops	600	900	1100	1300
Manufacturing	300	470	590	720
Manufacturing storage	1180	1800	2240	2690
Library	1500	2250	2250	--
School	285	360	410	450

Table C4: Fire load density for different occupancies according to BSI [7] and [23]

For the processing of the data it is often more convenient to use a distribution function. For the fire load as an accidental load a Gumbel-distribution [16] with a variation coefficient of V = 0,3 is often used.

Mean: $\mathbf{m} = u + \frac{\gamma}{\alpha} = \mathbf{420\ MJ/m^2}$

Coefficient of variation: V = 0,3

Standard deviation: $\sigma = \frac{\pi}{\alpha \cdot \sqrt{6}} = 420\ \text{MJ/m}^2 \cdot 0{,}3 \approx \mathbf{130\ MJ/m^2}$

$\gamma = 0{,}577216$

$\alpha = \frac{\pi}{\sigma \cdot \sqrt{6}} = \frac{\pi}{\mathbf{0{,}3 \cdot 420} \cdot \sqrt{6}} = 0{,}01018$

$u = \mu - \frac{\gamma}{\alpha} = 420 - \frac{\mathbf{0{,}577216}}{\mathbf{0{,}01018}} = 363{,}3$

Note: This distribution does not exactly fit to the values given in Table C4. (e.g. cumulative function for q = 570 MJ/m² is F(q)= exp(-exp(-α(q-u))) = exp(-exp(-0,01018 · (570-363,3))) = 88,52 % and not 80% as in Table C4).

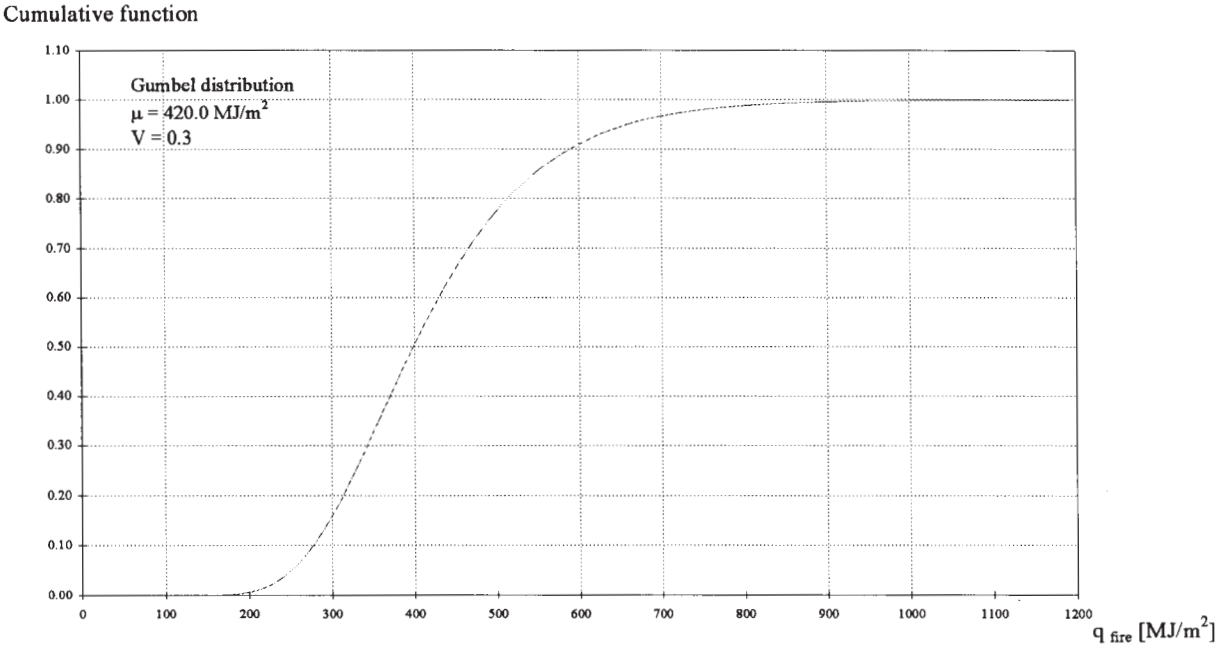


Figure C5: Cumulative distribution of the fire load in a standard office

Table C5 gives the Gumbel-distribution for the fire load with the same mean values as in Table C4 and a Variation coefficient of V = 0,3. This table corresponds also to the Table 4-3 of the WG3 report [29].

	mean	standard deviation	V	80%	90%	95%	Gumbel parameters	
	[MJ/m²]	[MJ/m²]		[MJ/m²]	[MJ/m²]	[MJ/m²]	α	u
Dwelling	780	234	0,3	948	1085	1215	0,00548	674,69
Hospital	230	69	0,3	279	320	358	0,01859	198,95
Hotel	310	93	0,3	377	431	483	0,01379	268,15
Office (standard)	**420**	**130**	0,3	511	584	655	0,01018	363,29
Shops	600	180	0,3	729	834	935	0,00713	518,99
Library	1500	450	0,3	1823	2086	2338	0,00285	1297,48
School	285	86	0,3	347	396	444	0,01500	246,52

Table C5: Fire load density for different occupancies and V = 0,3

For the calculations of the case study this Gumbel distribution will be used.

5.3.4 VENTILATION CONDITIONS

The temperature in a room fire is strongly influenced by the ventilation condition. If there is not enough air then the fire will be ventilation controlled, if there is much air the temperatures will be reduced by the mixing of the hot gases with the cold air. In a simplified way the ventilation conditions can be expressed by the opening factor.

Opening factor: $O_f = \frac{A_v \cdot \sqrt{h_w}}{A_t}$

with A_v: area of the vertical openings [m^2]
A_t: total area of the floor, walls and ceiling including all the
h_w: height of the vertical openings [m]

5.3.5 NOMINAL TIME-TEMPERATURE CURVES

The most important nominal time temperature curve is the ISO 834 standard fire curve.

The standard fire curve is defined as: $\theta_{max,gas} = 20 + 345 \cdot \log_{10}(8 \cdot t + 1)$ [8]

It is very similar to the ASTM and Japan standard fire curve. Other nominal fire curves are given in [8].

5.3.6 PARAMETRICAL TIME-TEMPERATURE CURVES

For ventilation controlled fires $0,02 < O_f < 0,10$ (0,2 according to the limit of EC 1 [8]) the time temperature curve is given in Annex B of ENV 1991-2-2 [8] and can be calculated to:

$$\theta_{max,gas} = 1325 \cdot \left(1 - 0{,}324 \cdot e^{-0,2 \cdot t_{max}} - 0{,}204 \cdot e^{-1,7 \cdot t_{max}} - 0{,}472 \cdot e^{-19 \cdot t_{max}}\right) \text{ [8] (B.1)}$$

with $q_{t,d} = q_{f,d} \cdot \left[A_f / A_t \right]$ [8] Annex B (B.1)

$$t_{max} = \frac{0{,}00013 \cdot q_{t,d} \cdot \Gamma}{O_f}$$

$$O_f = \frac{A_v \cdot \sqrt{h_w}}{A_t} \qquad \text{but: } 0{,}02 < O_f < 0{,}20$$

$$b = \sqrt{\rho \cdot c \cdot \lambda}$$

$$\Gamma = (O_f / b)^2 / (0{,}04/1160)^2$$

Note: Annex B [8] should be improved for fuel bed controlled fires and layered walls.

5.3.7 GAS TEMPERATURE SIMULATIONS WITH COMPUTER MODELS

The gas temperature can be simulated in time steps by computer models. For structural design only severe fires (e.g. mostly post flash over fires) are relevant which can be modelled satisfactorily with simple one-zone models [26 and 27].

5.4 STEEL TEMPERATURES

From the gas temperature the steel temperature can be calculated on the basis of the radiative and convective heat flux [1, 8 and 9]. An important parameter is the section factor A_m / V for unprotected steel or the thermal section factor (A_p / V) / (λ_p / d_p) for protected steel.

5.4.1 UNPROTECTED STEEL

The heating of unprotected steel is delayed to the gas temperature depending on the massivity factor A_m/V [9].

For an equivalent uniform temperature distribution in the cross-section, the increase of temperature in an unprotected steel member during the time interval Δt can be calculated from:

$$\Delta\theta_{a,t} = \frac{A_m/V}{c_a \cdot \rho_a} \cdot \dot{h}_{net,d} \cdot \Delta t \quad [9]\ (4.21)$$

with $\Delta t \leq 5$ sec [9] (chapter 4.2.5)

$c_a = 600$ J/kgK as a first assumption [9] (chapter 3.3.1.2)

$\rho_a = 7850$ kg/m^3 [9] (chapter 3.2.2)

$$\dot{h}_{net,d} = \gamma_{n,c} \cdot \dot{h}_{net,c} + \gamma_{n,r} \cdot \dot{h}_{net,r} \qquad [8]\ (\text{chapter } 4.2.1)$$

$$\dot{h}_{net,c} = a_c \cdot (\theta_g - \theta_m) \quad [8]\ (\text{chapter } 4.1)$$

$$\dot{h}_{net,r} = \varphi \cdot \varepsilon_{res} \cdot 5{,}67 \cdot 10^{-8} \cdot \left[(\theta r + 273)^4 - (\theta_m + 273)^4\right]$$

$$\gamma_{n,c} = \gamma_{n,r} = 1{,}0$$

A_m/V: section factor

5.4.2 PROTECTED STEEL

The temperature increase in a protected steel member during the time interval Δt may be calculated from:

$$\Delta\theta_{a,t} = \frac{\lambda_p \cdot A_p/V}{d_p \cdot c_a \cdot \rho_a} \cdot \frac{(\theta_{g,t} - \theta_{a,t})}{\left(1 + \phi/3\right)} \cdot \Delta t - \left(e^{\phi/10} - 1\right) \cdot \Delta\theta_{g,t} \quad [9]\ (4.22)$$

with $\Delta t \leq 5$ sec

$c_a = 600$ J/kgK (as a first assumption) [9] (chapter 3.3.1.2)

$\rho_a = 7850$ kg/m^3 [9] (chapter 3.2.2)

$\theta_{a,t}$: steel temperature at time t [°C]

$\theta_{g,t}$: gas temperature at time t [°C]

$\Delta\theta_{g,t}$: the increase of the ambient gas temperature during the time interval Δt [°C]

A_m/V : section factor

5.5 FIRE RESISTANCE OF PROTECTED AND UNPROTECTED STEEL MEMBERS

5.5.1 LOAD LEVEL AND CRITICAL TEMPERATURE

With increasing steel temperature the yield stress decreases. If in a beam the plastic moment for a temperature θ has decreased to the applied moment collapse will occur. The steel temperature at collapse is called critical temperature θ_{crit}. It can be calculated from the load level μ_0 e.g. the relation between the action effect and the resistance at room temperature.

$\mu_0 = M_{d,fire} / M_{R,fire,t=0}$

From the load level μ_0 the critical temperature θ_{crit} is calculated as:

$$\theta_{a,crit} = 39{,}19 \cdot \ln\left[\frac{1}{0{,}9674 \cdot \mu_0^{3{,}833}} - 1\right] + 482 \quad [9]\ (4.18)$$

5.5.2 REDUCTION FACTORS FOR THE STRESS-STRAIN RELATIONSHIP

The reduction factors k_θ for the stress-strain relationship of structural steel at elevated temperatures is defined on the basis of the above formula for the critical temperature in [9] as:

$$k_{y,\theta} = \frac{1{,}0087}{\left(e^{\left(\frac{\theta-482}{39{,}19}\right)} + 1\right)^{0{,}2609}} \quad [15]\ (2b)$$

With a similar exponential function also the relationship for the modulus of elasticity can be approximated [19]:

$$k_{E,\theta} = \exp\left[-\frac{\theta^{2,5} - 20^{2,5}}{530^{2,5}}\right] + 0{,}2 \cdot \exp\left[-\frac{(\theta - 500)^2}{100^2}\right] \quad [19]$$

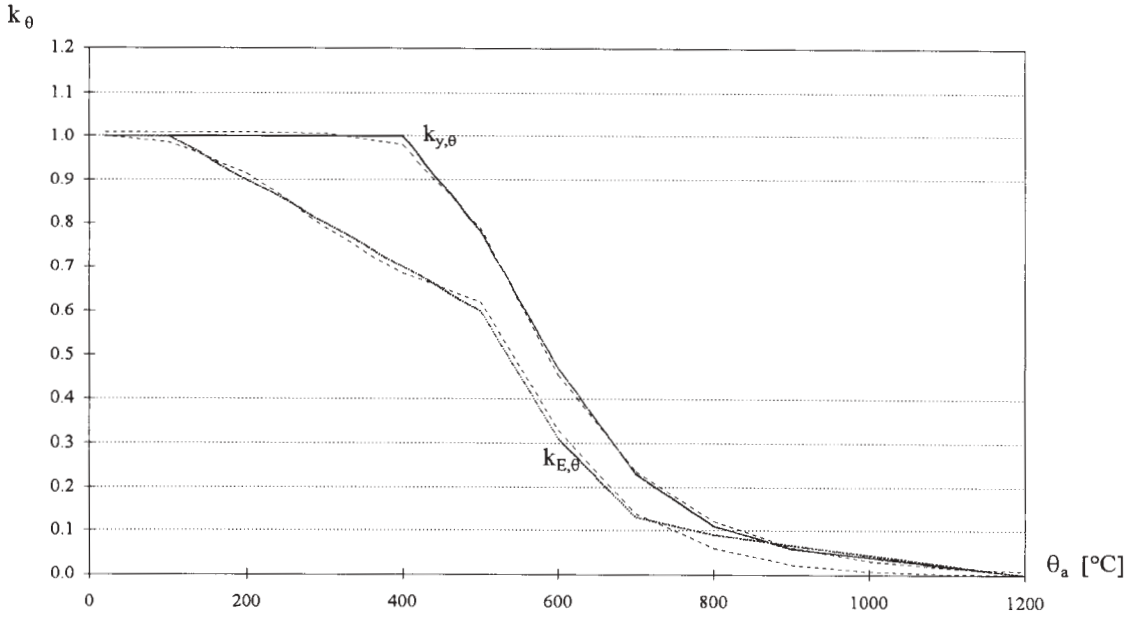


Figure C6: Reduction factors k_θ for structural steel at elevated temperatures [15 and 19] (approximations as dotted lines)

5.6 FAILURE PROBABILITY OF A STRUCTURAL ELEMENT

The conditional failure probability $p_{f,fi}$ of a structural element to resist a severe fire can be calculated by using a FORM analysis. The main parameters are introduced as variables and also model uncertainties may be introduced with a model variable. More detailed information is given in [12]. An easy to use software VaP is described in [3] and was used for the case study. As an alternative the calculation of the failure probability can be performed using a Monte Carlo analysis or other variable processing methods

The following density function and parameter were chosen for the analysis of the case study.

5.6.1 PROBABILITY DENSITY FUNCTION (PDF) FOR EACH VARIABLE (COLD)

Self weight:

G_B: law: Gaussian
nominal value : 50% fractile [6] chapter 4.2
$V_G = 0,1$ [4] chapter 9.3.1
m_G = nominal value
$\sigma_G = m_G \cdot V_G$

Variable load:

N_B: law: Gumbel Type I [4] chapter 9.3.1
nominal value : 95% fractile [6] chapter 4.2
$V_N = 0,3$ [4] chapter 9.3.1
m_N = nominal value / 1,56
$\sigma_N = m_N \cdot V_N$

Structural steel:

f_y: law: lognormal
nominal value : 5% fractile
$V_R = 0,052$ [5] (Table 2.3)
$m_R = e^{1,645 V_R} \cdot$ nominal value [5] (2.5)
$\sigma_R = m_R \cdot V_R$

5.6.2 PROBABILITY DENSITY FUNCTION (PDF) FOR EACH VARIABLE (CASE OF FIRE)

According to ENV 1991-2-2 [8] the nominal value for the fire load is given usually as the 80% fractile. Fire load [28]:

q: law: Gumbel Type I
nominal value : 80% fractile [8] Annex D.2.2
$V_N = 0,3$
m_N = nominal value / 1,3
$\sigma_N = m_N \cdot V_N$

5.7 ACCEPTANCE CRITERIA

5.7.1 TARGET RELIABILITY INDEX β

The definition of a target value of the reliability index β is technically the most straightforward approach (e.g. probability of structural failure per year for an individual member of the public). The verification of β for a structural element in fire contains in a first step the calculation of the conditional failure probability $p_{f,fi}$ according chapter 5.6.

$p_f = p_{severe,fire} \cdot p_{f,fi}$

p_f : structural failure probability from a fire free status (unconditional failure probability) (chapter 5.6)
$p_{severe,fire}$: probability to have a severe fire (see Table 3)
$p_{f,fi}$: structural failure probability given a severe fire (conditional failure probability)

The conditional failure probability p_f can then be compared to a general target β-value. Eurocode 1 [6] assumes in Annex A.2 implicitly that the target failure probability of the structure p_f is lower than the target failure probability of **$7,25 \cdot 10^{-5}$ per lifetime** of the building, which is equivalent to a reliability index $\beta = 3,8$.

But it should be noted that the β-value and the corresponding failure probability are formal or national numbers, intended primarily as a tool for developing consistent design rules, rather than giving a description of the structural failure frequency for a given building.

5.7.2 COMPARATIVE APPROACH

The comparative approach is usually the easiest way to communicate an acceptable safety level. The solutions defined in prescriptive regulations are considered as acceptable and are used as a benchmark. The disadvantage of the comparative approach is that the absolute level of safety is not clearly defined in prescriptive codes and may differ from case to case.

A comparative approach was used in the study in chapter 6.

6 APPLICATION OF THE PROBABILISTIC NATURAL FIRE SAFETY CONCEPT

6.1 FIRE OCCURRENCE AND FIRE GROWTH

From Table C2 the probability of a fire to grow to a severe fire is taken as $0,4 \cdot 10^{-6}$ / ($m^2 \cdot$ year) by assuming that a fire with a loss > 50.000 CHF corresponds to a severe fire (see Table C3) able to threaten the structure.

6.1.1 PROBABILITY OF A SEVERE FIRE FOR CODE DESIGN

$p_{severe,fire} = p_1 \cdot A^x \cdot n = 0,4 \cdot 10^{-6} / (m^2 \cdot year) \cdot 600\ m^2 \cdot 50\ years = 0,012$ / lifetime

with $p_1 = 0,4 \cdot 10^{-6} / (m^2 \cdot year)$
$A = 30 \cdot 20 = 600\ m^2$
$x = 1,0$
$n = 50$ years

6.1.2 PROBABILITY OF A SEVERE FIRE FOR EXISTING DESIGN

$p_{severe,fire} = p_1 \cdot A^x \cdot n \cdot p_M = 0,4 \cdot 10^{-6} / (m^2 \cdot year) \cdot 1600\ m^2 \cdot 50\ years \cdot 1/8 = 0,004$ / lifetime

with $p_1 = 0,4 \cdot 10^{-6} / (m^2 \cdot year)$
$A = 80 \cdot 20 = 1600\ m^2$
$X = 1,0$
$n = 50$ years
$p_M = 1/8$

(The earlier alarm due to the detection system is assumed to increase the fire fighting efficiency. The influence is estimated by a factor of 1/8, see Table 8 of [25] and [28])

6.2 MECHANICAL ACTIONS

The mechanical actions and structural system are given in chapter 4.1.1.

Beam: $M_{d,fire} = \frac{q_{d,fire} \cdot l^2}{11,67} = \frac{54,7 \cdot 6,66^2}{11,67} = 207,9$ kNm

Column: $S_{d,storey} = 1,0 \cdot (5 \cdot 4,3\ kN + 4 \cdot 177,2\ kN) + 0,5 \cdot (4 \cdot 275,7\ kN) = 1281,7$ kN

6.3 THERMAL ACTIONS

6.3.1 FIRE LOAD

The fire load is taken according chapter 5.3.3.

6.3.2 VENTILATION CONDITIONS

It is assumed that for a severe fire all windows will be broken.

6.3.2.1 Opening factor for code design

The opening factor for the code design (see Figure C2) can be calculated to:

Room: $b = 20{,}0$ m
$\ell = 30{,}0$ m
$h = 3{,}2$ m
$A = 20{,}0 \cdot 30{,}0 = 600$ m^2
$A_t = (2 \cdot 600) + (20{,}0 + 30{,}0) \cdot 2 \cdot 3{,}2 = 1520$ m^2

Window: $b_w = 80{,}0$ m
$h_w = 3{,}0$ m
$A_v = 240{,}0$ m^2

Opening factor: $O_f = \frac{A_v \cdot \sqrt{h_w}}{A_t} = \frac{240 \cdot \sqrt{3}}{1520} = 0{,}273$

6.3.2.2 Opening factor for existing design

The opening factor for the existing design (see Figure C3) can be calculated to:

Room: $b = 20{,}0$ m
$\ell = 80{,}0$ m
$h = 3{,}2$ m
$A_f = 20{,}0 \cdot 80{,}0 = 1600$ m^2
$A_t = (2 \cdot 1600) + (20{,}0 + 80{,}0) \cdot 2 \cdot 3{,}2 = 3840$ m^2

Window: $b_w = 200{,}0$ m
$h_w = 3{,}0$ m
$A_v = 600{,}0$ m^2

Opening factor: $O_f = \frac{A_v \cdot \sqrt{h_w}}{A_t} = \frac{600 \cdot \sqrt{3}}{3840} = 0{,}271$

6.3.3 PARAMETRICAL TIME-TEMPERATURE CURVES

Annex B [8] is not applied as the opening factor for both designs are larger than the range of application. After the breaking of the windows the fire will be fuel bed controlled.

6.3.4 GAS TEMPERATURE SIMULATIONS WITH ONE-ZONE MODELS

The modified one-zone model fire simulation program BSBG [26] was used to calculate the time temperature curve with the following parameters:

Fire load density: $q_{d,\,fire} = 570$ MJ/m^2 (80% fractile) [8]

Max. RHR: $\dot{q}_{d,\,fire} = 320 \frac{kW}{m^2}$

Fire spread: $v = 0{,}5$ m/min (in each direction starting in the middle of the room)

Combustion rate: 5 $\frac{kg_{air}}{kg_{wood}}$

In the BSBG program the maximum rate of heat release is reduced according to the available oxygen for ventilation controlled situations. If flashover conditions are reached then the fire spread is increased to reach rapid full room involvement. The maximum RHR $q'_{d,\,fire}$ = 320 kW/m^{2}is conservatively higher chosen than the value given for offices of 250 kW/m^2 in [7].

6.3.4.1 Gas temperature for code design

For the room geometry given in Figure C2 (window height h_w = 2,5 m) and the above input parameters the time temperature curve in Figure C7 is found. For a comparison the influence of other window heights (1,5 m, 2 m, 3 m) and the ISO curve as well as for Annex B with a limited opening factor of O_f = 0,2 is shown.

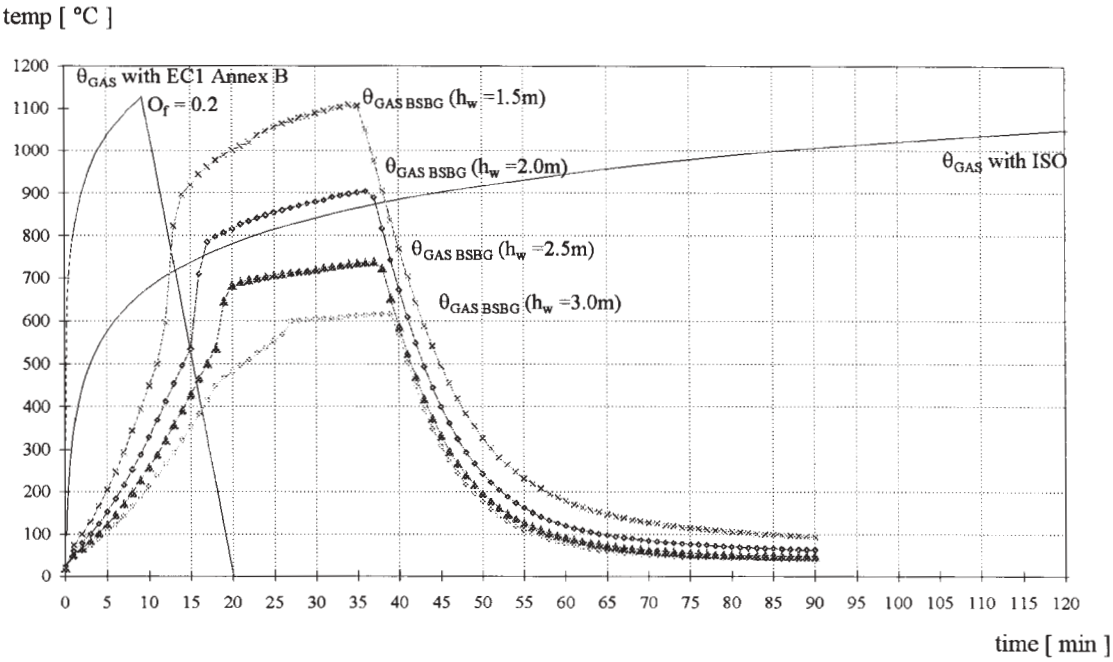


Figure C7: Gas temperature curve for the fire compartment size of 20 m · 30 m and different window heights

6.3.4.2 Gas temperature for existing design

For the room geometry given in Figure C3 (window height h_w = 2,5 m) and the above input parameters the time temperature curve in Figure C8 is found. For a comparison the influence of other window heights (1,5 m; 2 m; 3 m) and the ISO curve as well as for Annex B with a limited opening factor of O_f = 0,2 is shown.

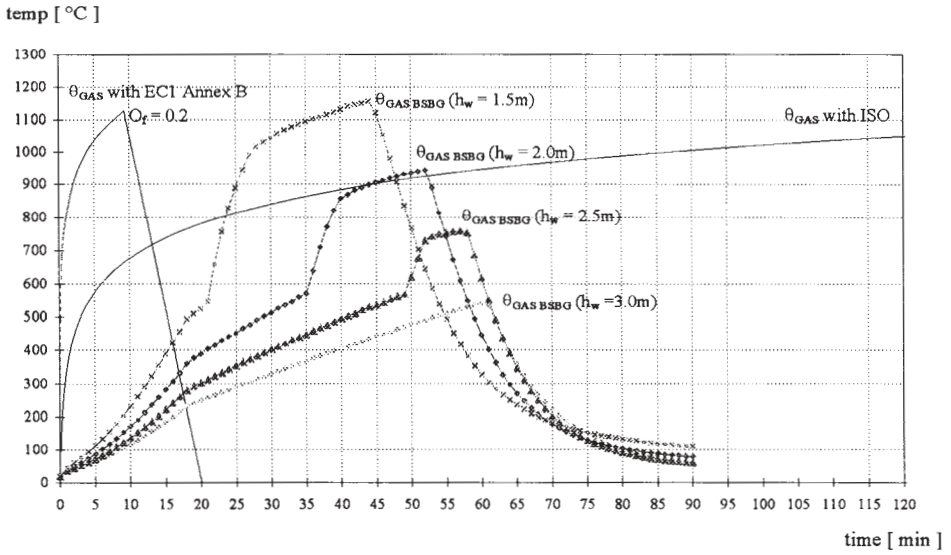


Figure C8: Gas temperature curve for the fire compartment size of 20 m / 80 m and different window heights

6.4 STEEL TEMPERATURES

From the gas temperatures (chapter 6.3.4) the steel temperatures can be calculated according chapter 5.4.

6.4.1 CODE DESIGN

For the code design the beam and the column have an ISO fire resistance of 60 minutes as shown in chapter 4.2.1 and 4.2.2. The temperatures in the steel beam are given in Figure C9 and Figure C10.

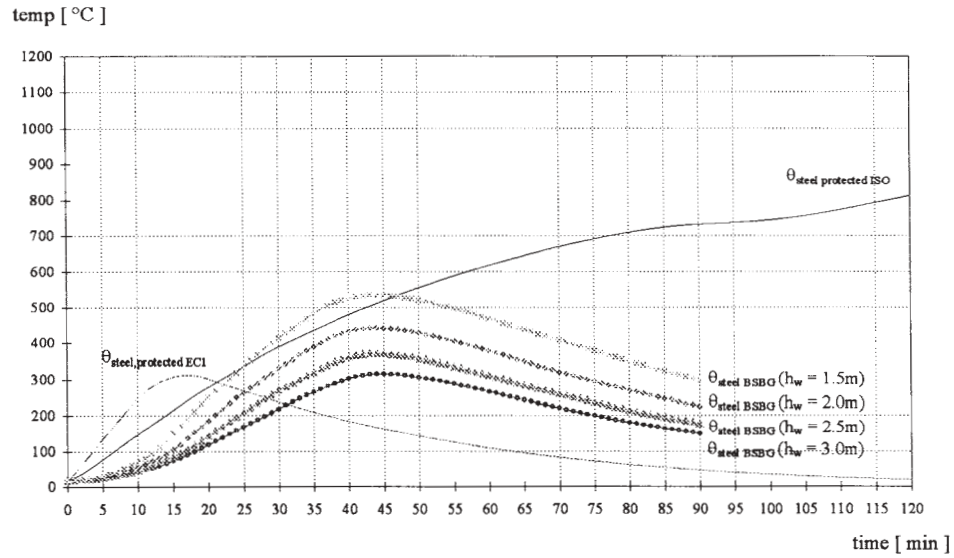


Figure C9: Development of the steel temperature for a fire load of 570 MJ/m^2 of R60 protected IPE 400 beam, with $(A_p/V) \cdot (\lambda_p/d_p) = 1740$ m^{-1}, for the small office given in Figure C2 according to the code design

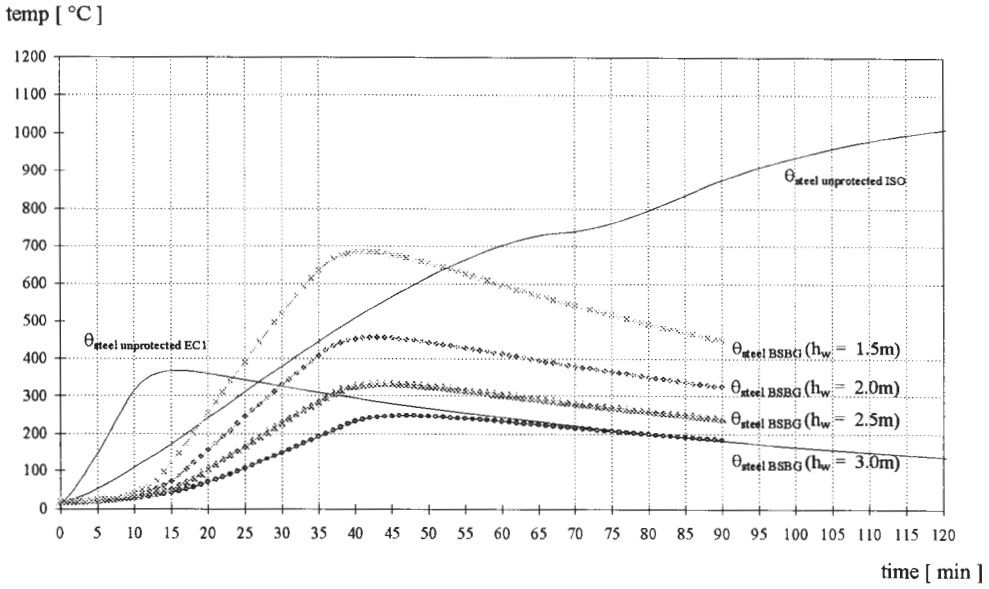


Figure C10: Development of the steel temperature for a fire load of 570 MJ/m² a solid column ∅ 190 mm, with A_m/V = 21,1 m^{-1} (R60 see chapter 4.2.2), for the small office given in Figure C2 according to the code design

The maximum steel temperatures in function of the fire load were calculated with the program BSBG for the small office (window height h_w = 2,5 m) and fitted with a polynom: Beam R60 $\theta_{max} = -1 \cdot 10^{-11}q^4 + 1 \cdot 10^{-7}q^3 - 0{,}0003q^2 + 0{,}7q + 75{,}6$

Column R60 $\theta_{max} = -2 \cdot 10^{-12}q^4 + 4 \cdot 10^{-8}q^3 - 0{,}0002q^2 + 0{,}7q + 6{,}5$

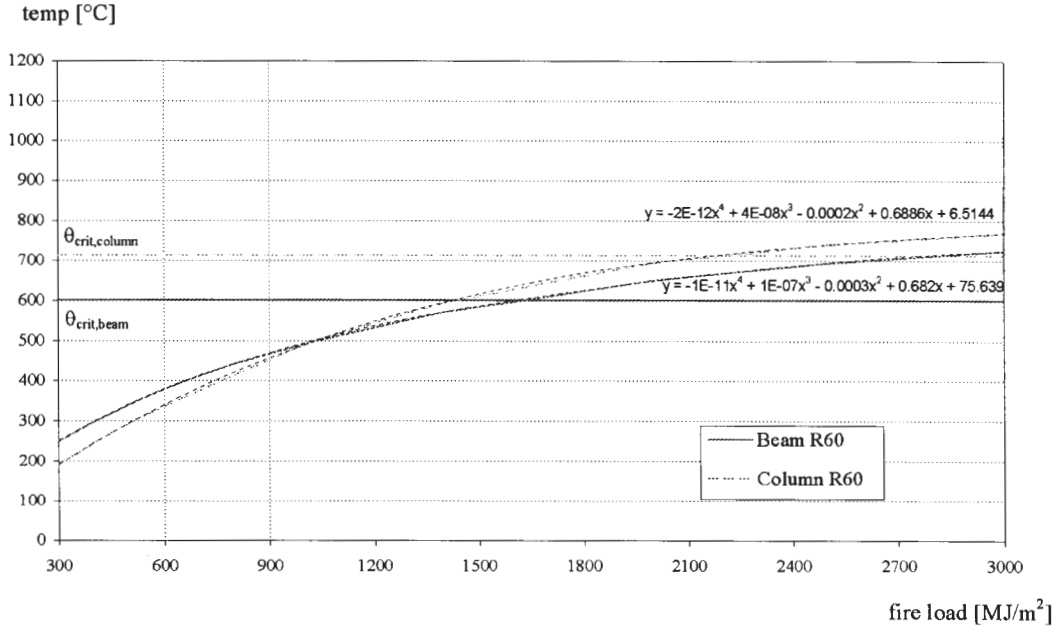


Figure C11: Fitted curve for the increase of the maximum steel temperature for protected steel beam R60 and the solid column in function of the fire load $q_{d,fire}$ (h_{window} = 2,5m)

6.4.2 EXISTING DESIGN

For the existing design the beam and the column have a fire resistance of R30 as given in chapter 4.2.1 and 4.2.2. The temperatures in the steel members are given in Figures C12 and C13.

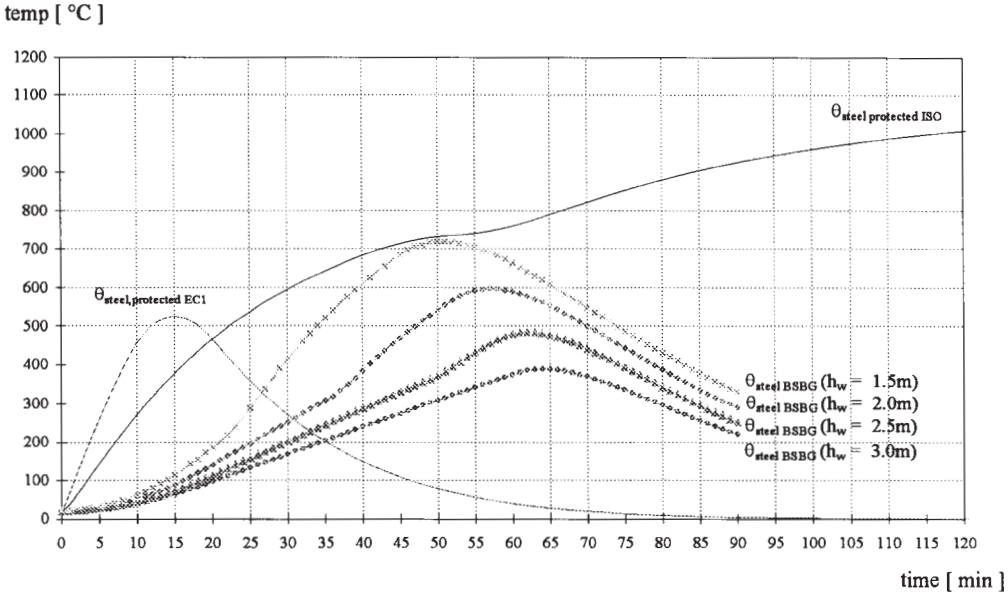


Figure C12: Development of the steel temperature of the R30 protected IPE 400 beam, for the fire load of 570 MJ/m^2 and the large office according to the existing design given in Figure C3

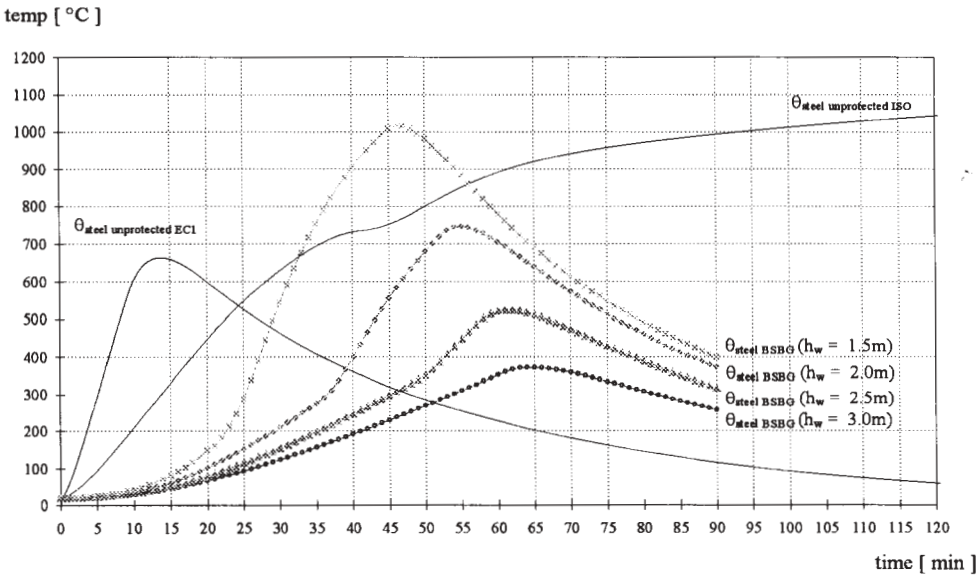


Figure C13: Development of the steel temperature of hollow core column ROR ⌀ 298,5 mm (t = 20mm), with $A_m/V = 50\ m^{-1}$ (R30 see chapter 4.2.2), for the fire load of 570 MJ/m^2 and the large office according to the existing design given in Figure C3

The development of the maximum steel temperature as a function of the fire load was calculated with the one-zone model BSBG for the large office with a window height h_w = 2,5 m and fitted with a polynom:

Beam R30 $\quad \theta_{max} = -2 \cdot 10^{-11} q^4 + 2 \cdot 10^{-7} q^3 - 0{,}0006 q^2 + 0{,}9q + 101{,}5$

Column R30 $\quad \theta_{max} = -4 \cdot 10^{-11} q^4 + 3 \cdot 10^{-7} q^3 - 0{,}0011 q^2 + 1{,}6q + 84{,}7$

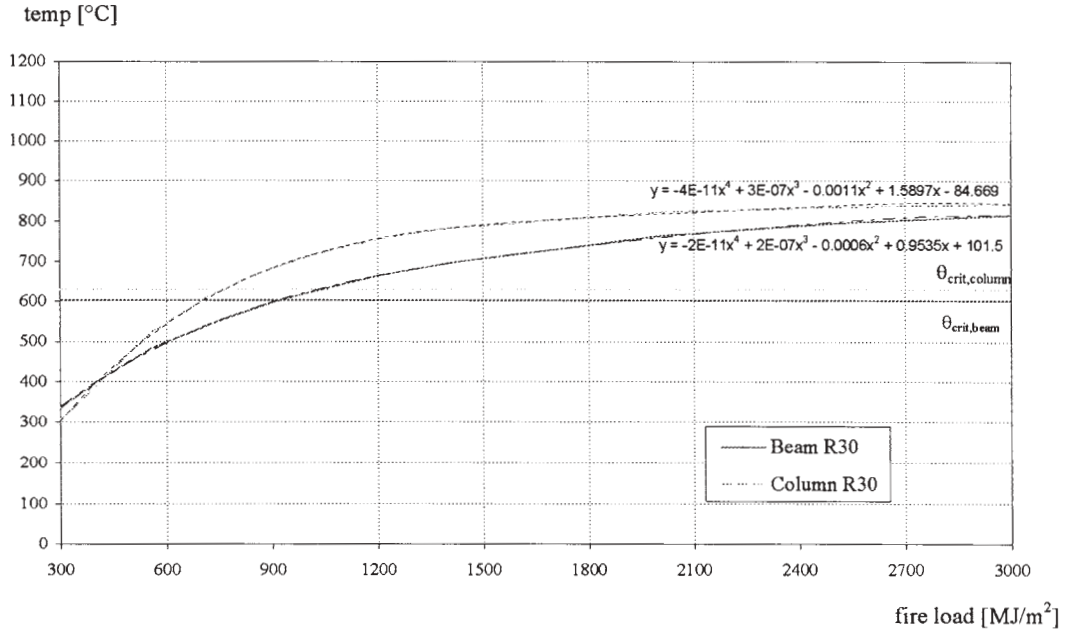


Figure C14: Fitted curve for the increase of the maximum steel temperature for the large office (R30) in function of the fire load $q_{d,fire}$ (h_{window} = 2,5m) and the critical temperatures for the beam and the column

6.5 FAILURE PROBABILITIES

With the steel temperatures as a function of the fire load the failure probability of the beam and column can be calculated. The loads and the resistance (f_y) are introduced as variables.

6.5.1 PROBABILITY DENSITY FUNCTION (PDF)

The variables with their probability density functions that have been used in the VaP [3] calculations in case of fire are:

	nominal	fractile	m	σ	V	Law
G_B	41,4	50%	41,4	4,14	0,1	N
N_B	26,6	95%	17,1	5,13	0,3	GL
f_y	355	5%	386,7	20,11	0,052	LN
q	511	80%	420	130	0,3	GL

Table C6: Variables for the beam R30 and R60 (see chapter 3.1.6 and 5.3.3)

	nominal	fractile	m	σ	V	Law
G_C	1124,9	50%	1124,9	112,49	0,1	N
N_C	764,8	95%	490,3	147,1	0,3	GL
f_y	235	5%	255,987	13,3	0,052	LN
q	511	80%	420	130	0,3	GL

Table C7: Variables for the hollow core column R30 (see chapter 3.2.5 and 5.3.3)

	nominal	fractile	m	σ	V	Law
G_C	1124,9	50%	1124,9	112,49	0,1	N
N_C	764,8	95%	490,3	147,1	0,3	GL
f_y	295	5%	321,35	16,7	0,052	LN
q	511	80%	420	130	0,3	GL

Table C8: Variables for the solid column R60 (see chapter 4.2.2 and 5.3.3)

6.5.2 LIMIT STATE FUNCTION

6.5.2.1 Limit state function for the beam in case of fire

The resistance of a steel beam in case of fire is calculated as followed:

$R_{d,fi} = M_{d,fi} = k_{y,\theta} \cdot f_y \cdot Z$

The limit state function is defined as: [17]

$$G = R_{pl} - \left(\frac{(N_B + G_B)\cdot l^2}{11{,}67}\right) = (k_{y,\theta} \cdot f_y \cdot Z)/1000 - \left(\frac{(N_B + G_B)\cdot l^2}{11{,}67}\right)$$

$$= \left(\frac{1}{0{,}9674 \cdot \left(1 + e^{\left\{\frac{\theta - 482}{39{,}19}\right\}}\right)}\right)^{\left(\frac{1}{3{,}833}\right)} *(f_y \cdot Z)/1000-((N_B+G_B)*L\text{^}2)/11{,}67$$

and therefore the limit state function can be written as:

G=(f$_y$/1000)*Z*(1/(0,9674*(1+EXP((TEMP-482)/39,19))))^(1/3,833) (N$_B$+G$_B$)/11,67*L^2

The time temperature curve TEMP [°C] are introduced by a polynomial fitting curve of the steel temperature curve (see chapter 6.4.1 and 6.4.2) for h_{window} = 2,5 m.

Beam R30 $\theta_{max} = -2 \cdot 10^{-11} q^4 + 2 \cdot 10^{-7} q^3 - 0{,}0006 q^2 + 0{,}9q + 101{,}5$

Beam R60 $\theta_{max} = -1 \cdot 10^{-11} q^4 + 1 \cdot 10^{-7} q^3 - 0{,}0003 q^2 + 0{,}7q + 75{,}6$

6.5.2.2 Limit state function for the column in case of fire

The design buckling resistance for compression members can be calculated according ENV 1993-1-2 [9] to:

$$R_{fi,d,\theta max} = \frac{\kappa_{c,\theta max} \cdot \left[k_{y,\theta max} / 1{,}2 \right] \cdot f_y}{\gamma_{M,fire}} \quad \text{[9] (chapter 4.2.3.2)}$$

with $\gamma_{M,fire} = 1{,}0$

$$\kappa_{c,\theta max} = \frac{1}{\varphi + \sqrt{\varphi^2 - \bar{\lambda}_{\theta max}^{\,2}}}$$

α_i depending on the buckling curve [31] (3 252 4)

$$\varphi = 0{,}5 \cdot \left[1 + \alpha \cdot \left(\bar{\lambda}_{\theta max} - 0{,}2 \right) + \bar{\lambda}_{\theta max}^{\,2} \right]$$

$$\bar{\lambda}_{\theta max} = \bar{\lambda}_{fi,0} \cdot \sqrt{k_{y,\theta max} / k_{E,\theta max}}$$

(As a simplification $\bar{\lambda}_{\theta max}$ can be taken as $\bar{\lambda}_{\theta max} = 1{,}2 \cdot \bar{\lambda}_{20°C}$)

$$\bar{\lambda}_{fi,0} = \frac{\ell_{k,fire}}{\sqrt{I/A} \cdot \pi \cdot \sqrt{E/f_y}}$$

Note: The results of the research 7210-SA/316/515/618/931 "Buckling Curves in Case of Fire" should be used in the future and leads to higher $R_{fi,d,\theta\,max}$

Including the geometrical data for the column and the reduction factors (see chapter 5.5.2) the limit state function can be written as:

G = $R_{fire,d}$ - (N_C + G_C)
=(((1/((0,5*(1+0,49*(((lk/i/(π*((E/fy)^0,5)))*(((1/(0,9674*(1+EXP((TEMP482)/39,19))))^(1/3,833)/((EXP(-((TEMP^2,5-20^2,5)/(530^2,5))))+(0,2*EXP(-(((TEMP-500)^2)/(100^2))))))^0,5))-0,2)+((lk/i/(π*((E/fy)^0,5)))*(((1/(0,9674*(1+ EXP((TEMP-482)/39,19))))^(1/3,833)/((EXP(-((TEMP^2,5-20^2,5)/(530^2,5))))+(0,2*EXP(-(((TEMP-500)^2)/(100^2))))))^0,5))^2))+((0,5*(1+0,49*(((lk/i/(π*((E/fy)^0,5)))*(((1/(0,9674*(1+EXP((TEMP-482)/39,19))))^(1/3,833) /((EXP(-((TEMP^2,5 -20^2,5)/(530^2,5))))+ (0,2*EXP(-(((TEMP-500)^2)/(100^2))))))^0,5))-0,2)+((lk/i/(π*((E/fy)^0,5)))*(((1/(0,9674*(1+EXP((TEMP-482)/39,19))))^(1/3,833)/((EXP(-((TEMP^2,5-20^2,5)/(530^2,5))))+(0,2*EXP(-(((TEMP-500)^2)/(100^2))))))^0,5))^2))^2-((lk/i/(π*((E/fy)^0,5)))*(((1/(0,9674*(1+EXP((TEMP-482)/39,19))))^(1/3,833)/((EXP(-((TEMP^2,5-20^2,5)/(530^2,5))))+(0,2*EXP(-(((TEMP-500)^2)/(100^2))))))^0,5))^2)^0,5))/1,2)*A*fy*(1/(0,9674*(1+EXP((TEMP-482)/39,19))))^(1/3,833))-((NC + GC)*1000)

The time temperature curve TEMP [°C] is introduced by a polynomial fitting curve of the steel temperature curve (see chapter 6.4.1 and 6.4.2) for h_{window} = 2,5 m.

Column R30 $\theta_{max} = -4 \cdot 10^{-11} q^4 + 3 \cdot 10^{-7} q^3 - 0{,}0011 q^2 + 1{,}6q + 84{,}7$

Column R60 $\theta_{max} = -2 \cdot 10^{-12} q^4 + 4 \cdot 10^{-8} q^3 - 0{,}0002 q^2 + 0{,}7q + 6{,}5$

6.5.3 PROBABILISTIC FIRE RISK ANALYSIS

For the beam and the column the failure probability p_f and the reliability index β are calculated. Of special interest are the weighting factors α_i which show with which weight the corresponding variable participates in the value of the probability of failure and give therefore the type of failure mode (e.g. due to the variable load or the fire load).

6.5.3.1 Reliability for code design (R60)

With the geometrical characteristics of the **IPE 400 (d_p = 12 mm)**, the variables from Table C6, the limit state function from chapter 6.5.2.1 and the fitted steel temperature curves from chapter 6.4.1 a FORM analysis was performed:

Variables of G:			α	
L	D	6,660		
Z	D	1,310e+03		
N	GL	14,791	0,25	0,106
P	N	41,400	4,140	0,087
f_y	LN	5,956	0,052	-0,066
q	GL	361,493	0,010	0,988

For the R60 insulated IPE 400 beam ($(A_p/V) \cdot (\lambda_p/d_p)$ = 1.740 W/($m^3 \cdot$ K)) a reliability index β = 5,45 and a failure probability due to the fire load of $p_f = 6{,}52 \cdot 10^{-4}$ has been found. For a comparison a Monte Carlo Analysis of G was performed. For the R60 insulated IPE 400 beam a failure probability of $6{,}83 \cdot 10^{-4}$ was found for 10 Mio. Monte Carlo samples.

With the geometrical characteristics of the column **Ø 190**, the variables from Table C8, the limit state function from chapter 6.5.2.2 and the fitted steel temperature curves from chapter 6.4.1 a FORM analysis was done.

Variables of G:			α	
A	D	2,835e+04		
E	D	2,100e+05		
i	D	47,5		
l_k	D	1,480e+03		
N	GL	424,097	0,009	0,087
P	N	1,125e+03	112,49	0,066
f_y	LN	5,771	0,052	-0,042
q	GL	361,493	0,010	0,993

For the R60 unprotected column ∅ 190 (A_m / V= 21,1 W/(m^3 · K)) a reliability index β = 3,89 and a failure probability due to the fire load of $p_f = 5{,}06 \cdot 10^{-5}$ has been found. For a comparison a Monte Carlo Analysis of G was performed. For the R60 unprotected column ∅ 190 a failure probability of $5{,}2 \cdot 10^{-5}$ was found for 10 Mio. Monte Carlo samples.

6.5.3.2 Reliability for existing design (R30)

With the geometrical characteristics of the **IPE 400 (d_p = 5 mm)** beam, the variables from Table C6, the limit state function from chapter 6.5.2.1 and the fitted steel temperature curves from chapter 6.4.2 a FORM analysis was performed:

Variables of G:			α	
L	D	6,660		
Z	D	1,310e+03		
N	GL	14,791	0,250	0,201
P	N	41,400	4,140	0,143
f_y	LN	5,956	0,052	-0,113
q	GL	361,493	0,010	0,963

For the R30 insulated IPE 400 beam ((A_p/V) · (λ_p/d_p) = 4.176 W/(m^3 · K)) a reliability index β = 3,16 and a failure probability due to the fire load of $p_f = 7{,}97 \cdot 10^{-4}$ has been found. For a comparison a Monte Carlo Analysis of G was performed with 10 Mio. samples and a failure probability of $8{,}735 \cdot 10^{-4}$ was found. In this case the failure mode changes and the imposed load replaces the fire load as most important variable.

With the geometrical characteristics of the column **ROR ∅298,5 (t = 20 mm)**, the variables from Table C7, the limit state function from chapter 6.5.2.2 and the fitted steel temperature curves from chapter 6.4.2 a FORM analysis was done.

Variables of G:			α	
A	D	1,750e+04		
E	D	2,100e+05		
i	D	98,7		
l_k	D	1,480e+03		
N	GL	424,097	0,009	0,136
P	N	1,125e+03	112,49	0,105
f_y	LN	5,544	0,052	-0,076
q	GL	361,493	0,010	0,982

For the R30 unprotected column ROR ∅298,5 (t = 20 mm) (A_m / V = 50 W/(m^3 · K)) a reliability index β = 1,98 and a failure probability due to the fire load of $p_f = 2{,}37 \cdot 10^{-2}$ has been found. For a comparison a Monte Carlo Analysis of G was performed with 1 Mio. samples and a failure probability of $2{,}4 \cdot 10^{-2}$ was found.

6.6 ACCEPTANCE CRITERIA

6.6.1 SEVERE FIRE OCCURRENCE

According chapter 5.7.1 the unconditional failure probability p_f can be calculated

$$p_f = p_{severe,fire} \cdot p_{f,fi} = (p_1 \cdot A^x \cdot n \cdot p_M) \cdot p_{f,fi} = ((0{,}4 \cdot 10^{-6} / m^2 \cdot yr) \cdot A^x \cdot 50 \text{ years} \cdot p_M) \cdot p_{f,fi}$$

p_f : structural failure probability from a fire free status (unconditional failure probability, see chapter 5.6)
$p_{severe,fire}$: probability to have a severe fire (see chapter 6.1.1)
$p_{f,fi}$: structural failure probability given a severe fire (conditional failure probability, see chapter 6.5.3)

6.6.1.1 Code design

$$p_{severe,fire} = p_1 \cdot A^x \cdot n \cdot p_M = (0{,}4 \cdot 10^{-6} / m^2 \cdot yr) \cdot 600\ m^2 \cdot 50 \text{ years} \cdot 1{,}0 = 0{,}012$$

6.6.1.2 Existing design

$$p_{severe,fire} = p_1 \cdot A^x \cdot n \cdot p_M = (0{,}4 \cdot 10^{-6} / m^2 \cdot yr) \cdot 1600\ m^2 \cdot 50 \text{ years} \cdot (1/8) = 0{,}004$$

6.6.2 UNCONDITIONAL FAILURE PROBABILITY

6.6.2.1 Code design

R60 beam without active measures
IPE 400 (d_p = 12 mm) $p_f = 0{,}012 \cdot 6{,}52 \cdot 10^{-4} = 7{,}82 \cdot 10^{-6}$

R60 column without active measures
∅ 190 $p_f = 0{,}012 \cdot 5{,}06 \cdot 10^{-5} = 6{,}07 \cdot 10^{-7}$

6.6.2.2 Existing design

R30 beam with **detection system**
IPE 400 $p_f = 0{,}004 \cdot 7{,}97 \cdot 10^{-4} = 3{,}19 \cdot 10^{-6}$

R30 column with **detection system**
ROR ∅298,5 (t = 20 mm) $p_f = 0{,}004 \cdot 2{,}37 \cdot 10^{-2} = 9{,}48 \cdot 10^{-5}$

6.6.3 COMPARATIVE APPROACH

A comparative approach shows that the existing design with a structural fire resistance of 30 minutes and an additional detection system reaches a comparable safety level of structural reliability as given by the code design (structural fire resistance R60 and no active fire fighting measures).

6.6.4 TARGET RELIABILITY INDEX

The calculated unconditional failure probabilities from chapter 6.6.2 fulfil the requirement $p_{target} = 7{,}25 \cdot 10^{-5} > p_f$ (see chapter 5.7.1) (The p_f of the column in the existing design is close to the target. Note: it has to be mentioned that in the existing design the column was chosen as a solid column ∅ 177,8 but replaced for the example by a hollow core column to reach exactly 30 minutes fire resistance).

7 SWISS RISK EVALUATION METHOD

The Swiss risk evaluation [21] is an easy to apply rapid risk assessment method grading the most influential fire safety parameters in a building (see [18], pages 40 - 41). It allows to compare different fire safety concepts. It is not restricted to the question of structural resistance as it is for the moment with the NFSC-Method.

During the design of the office building in Langenthal it was used to compare the design with smoke detection but larger compartments and a reduced passive fire protection of 30 minutes to the code design with smaller compartments and one-hour fire protection of the structure.

According to the Swiss risk evaluation both concepts the alternative fire safety concept (R30 with 1.600 m^2 compartment size for each storey and smoke detection) and the code design (R60 with 600 m^2 compartment size for each storey and no active measures) are acceptable for this four storey building.

On the basis of this result the alternative concept with smoke detection and reduced fire protection was accepted by the fire authorities of the Canton of Berne.

7.1 EXISTING BUILDING (R30 AND SMOKE DETECTION SYSTEM)

	Swiss Risk Evaluation Method	
Company / Owner	Canton of Berne (district)	Assessment for the 4 th storey
Building	Realised in 1992	Location = office facilities
Building Type	**V/G** = voluminous / spacious	Fire safety concept = monitoring
Assessment made on a **V-based** type over the whole bldg. in order to simplify the calculation		

Fire loads of contents	3500 MJ (addition of 5 levels à 700)	Q	1,80
Combustibility of contents	normal	C	1,20
Smoke production index	low	R	1,00
Corrosive agents index	low	K	1,00
Combustibility of building	non-combustible	I	1,00
Number of storeys	ground floor plus 4 levels	E	1,65
Size of compartment	80 · 20 = 1.600 m^2 / whole storey	G	1,00
Potential danger		**P**	**3,56**
Portable extinguishers	in conformity with code	n_1	1,00
Indoor hydrants	in conformity with code	n_2	1,00
Water supply	in conformity with code	n_3	1,00
Distance between hydrants	> 70 m	n_4	1,00
Staff instruction	OK	n_5	1,00
Basic normal measures		**N**	**1,00**
Fire detection reliability	by automatic smoke detection device	s_1	1,45
Alarm transmission	automatic monitored transmission	s_2	1,20
Fire brigade class FB	well equipped fire brigade, top category 5-6	s_3	1,40
Call-out time class of FB	E < 15 min	s_4	1,00
Fire suppression devices	none, but fully equipped with detectors	s_5	1,00
Heat / smoke extraction	none	s_6	1,00
Active measures		**S**	**2,43**
Structural fire resistance	FR = 30	f_1	1,20
FR of facades	FR < 30 (windows > 2/3 of the exterior wall)	f_2	1,00
FR of slabs	FR = 30 / unprotected openings (between storeys)	f_3	1,00
Fire cell division	none	f_4	1,00
Passive measures		**F**	**1,20**
Fire loss expectations	low	**B**	**1,10**
Fire occurrence index	medium	**A**	**1,00**
Calculated fire risk		$R_{calculated}$	1,22
Human risk factor	normal	P_{HE}	1,00
Accepted fire risk	1,00 · 1,30 (basic value)	$R_{accepted}$	1,30
Global fire safety factor		γ	1,07

The proposed **fire safety concept is acceptable** and may well be used for a detailed design

7.2 BUILDING ACCORDING CODE DESIGN (STRUCTURAL CONCEPT R60)

	Swiss Risk Evaluation Method	
Company / Owner	Canton of Berne (district)	Assessment for the 4 th storey
Building	Realised in 1992	Location = office facilities
Building Type	**V/G** = voluminous / spacious	Fire safety concept = monitoring
Assessment made on a **V-based** type over the whole bldg. in order to simplify the calculation		

Fire loads of contents	3500 MJ (addition of 5 levels à 700)	Q	1,80
Combustibility of contents	normal	C	1,20
Smoke production index	low	R	1,00
Corrosive agents index	low	K	1,00
Combustibility of building	non-combustible	I	1,00
Number of storeys	ground floor plus 4 levels	E	1,65
Size of compartment	$30 \cdot 20 = 600\ m^2$	G	0,50
Potential danger		**P**	**1,78**
Portable extinguishers	in conformity with code	n_1	1,00
Indoor hydrants	in conformity with code	n_2	1,00
Water supply	in conformity with code	n_3	1,00
Distance between hydrants	> 70 m	n_4	1,00
Staff instruction	OK	n_5	1,00
Basic normal measures		**N**	**1,00**
Fire detection reliability	no specific precautions	s_1	1,00
Alarm transmission	no specific precautions	s_2	1,00
Fire brigade class FB	well equipped fire brigade, top category 5-6	s_3	1,40
Call-out time class of FB	E < 15 min	s_4	1,00
Fire suppression devices	none	s_5	1,00
Heat / smoke extraction	none	s_6	1,00
Active measures		**S**	**1,40**
Structural fire resistance	FR = 60	f_1	1,20
FR of facades	FR < 30 (windows > 2/3 of the exterior wall)	f_2	1,00
FR of slabs	FR = 60 / no openings between storeys	f_3	1,20
Fire cell division	none	f_4	1,00
Passive measures		**F**	**1,44**
Fire loss expectations	low	**B**	**0,88**
Fire occurrence index	medium	**A**	**1,00**
Calculated fire risk		$R_{calculated}$	**0,88**
Human risk factor	normal	P_{HE}	**1,00**
Accepted fire risk	1,00 · 1,30 (basic value)	$R_{accepted}$	**1,30**
Global fire safety factor		γ	**1,48**

The proposed **fire safety concept is acceptable** and may well be used for a detailed design

8 SIMPLIFIED NATURAL FIRE SAFETY CONCEPT

Structural collapse in fire is a rare event. It can only happen under the condition that there is a severe fire in the building. In a probabilistic way this is expressed by [28]:

$p_f = p_{severe,fire} \cdot p_{f,fi}$

- p_f: structural failure probability from a fire free status (unconditional failure probability)
- $p_{severe,fire}$: probability to have a severe fire
- $p_{f,fi}$: structural failure probability given a severe fire (conditional failure probability)

The probability of having a severe fire is given by (see chapter 5.2.2):

$p_{severe,fire} = p_1 \cdot t_{lifetime} \cdot A \cdot p_{FRI}$

- p_1: probability of fire **occurrence** for the relevant occupancy per year
- p_{FRI}: probability that this starting fire turns to a **flash-over** or a fully engulfed compartment fire
- $t_{lifetime}$: building lifetime (50 years)
- A: Room area (reference case: compartment area of 25 m^2)

8.1 DESIGN FIRE LOAD

For each action it is possible to define the partial safety coefficient γ which is the ratio between the design value S_d and the characteristic value S_k.

$$\gamma = \frac{S_d}{S_k}$$

Therefore the design fire load can be written as:

$q_{f,d} = \gamma_{q,f} \cdot q_{f,k}$

- $q_{f,d}$: design fire load
- $q_{f,k}$: characteristic value of the fire load (in our case 80% fractile)

The simplified approach [28] proposes the splitting of the global safety factor $\gamma_{q,f}$ into three coefficients $\gamma_{q,1}$ to consider the compartment size, $\gamma_{q,2}$ to consider the risk of fire activation, and γ_{ni} to take into account the influence of the active measures.

$\gamma_{q,f} = \gamma_{q,1} \cdot \gamma_{q,2} \cdot \gamma_{ni}$

- $\gamma_{q,f}$: global safety factor
- $\gamma_{q,1}$: Differentiation factor γ_{q1} – Influence of the compartment area
- $\gamma_{q,2}$: Differentiation factor γ_{q2} – Influence of the risk of fire activation
- γ_{ni}: Differentiation factor γ_{ni} – Influence of the active fire fighting measures

The product of the three factors $\gamma_{q,1}$, $\gamma_{q,2}$ and γ_{ni} leads to the global safety factor $\gamma_{q,f}$ which is multiplied with the characteristic fire load (here the 80% fractile) to give the design fire load considering implicitly the risk of fire and the influence of the active fire fighting measures. The natural fire curve is obtained by using this design fire to calculate the thermal action.

8.2 DIFFERENTIATION FACTOR γ_{Q1} – INFLUENCE OF THE COMPARTMENT AREA

When defining the partial differentiation factors in NFSC report [28] for the reference case a compartment area of 25m^2 was chosen. γ_{q2} in function of the compartment area is listed in Table C9.

Compartment area A [m^2]	γ_{q1}
25	1,00
250	1,25
2500	1,50
5000	1,60
10000	1,65

Table C9: Safety coefficients for different compartment areas

8.3 DIFFERENTIATION FACTOR γ_{Q2} – INFLUENCE OF THE RISK OF FIRE ACTIVATION

The buildings can be classified according to the danger of fire activation. A lower danger of activation reduces the probability that a fire starts by a factor N. From a reliability analysis based on the probability to have a fully engulfed compartment of $5 \cdot 10^{-7}$ per m^2 and year in schools, hotels and offices the influence on γ_{q2} of different occupancies shown in Table C10 were calculated.

Type of occupancy	Danger of activation	Reduction factor having a fully developed fire N	γ_{q2}
Museum, art gallery	Low	0,1	0,85
Hotel, school, office	Normal	1	1,00
Manufactory for machinery and engines	Average	10	$0,85^{-1} = 1,20$
Painting workshop Chemistry laboratory	High	100	$0,85^{-2} = 1,40$

Table C10: Danger of fire activation for different risk classes

8.4 DIFFERENTIATION FACTOR γ_{NI} – INFLUENCE OF THE ACTIVE FIRE FIGHTING MEASURES

In the same way the influence of active fire fighting measures can be quantified.

	Active measures	Reduction factor having a fully developed fire N	γ_{ni}
Automatic suppression	Sprinkler (S)	100	0,50
Manual fire suppression	Work fire brigade (WFB)	40	0,60
	Standard fire brigade (SFB)	10	0,73
	... + automatic fire detection by heat	2	0,90
	... + automatic fire detection by smoke	4	0,80
	... + automatic alarm and transmission to fire brigade	2	0,90

Table C11: Differentiation factors for active fire fighting measures

8.5 APPLICATION OF THE SIMPLIFIED NFSC-METHOD TO THE BUILDING ACCORDING TO THE CODE DESIGN

Global safety index: $\gamma_{q,f} = \gamma_{q,1} \cdot \gamma_{q,2} \cdot \gamma_{ni} = 1{,}28 \cdot 1{,}0 \cdot 1{,}0 = 1{,}28$

Compartment:	$\gamma_{q,1}$ =	1,28	A = 30 m · 20 m = 600 m^2
Danger of activation:	$\gamma_{q,2}$ =	1,0	normal risk
Fire fighting	γ_{ni} =	1,0	no special active measures

Design fire load:

$\mathbf{q_{f,d}} = \gamma_{q,f} \cdot q_{f,char} = 1{,}28 \cdot 570{,}0$ MJ/m^2 = **730 MJ/m^2**

$q_{f,d}$: design fire load

$q_{f,char} = 570$ MJ/m^2 characteristic value of the fire load (80% fractile)

The one-zone fire simulation program BSBG [26] was used to calculate the time temperature curve with the following parameters:

Fire load density: $q_{d,\,fire} = 730\ MJ/m^2$

Max. RHR: $\dot{q}_{d,\,fire} = 320\ \frac{kW}{m^2}$

Fire spread: v = 0,5 m/min (in each direction starting from the middle of the room)

Combustion ratio: $5\ \frac{kg_{air}}{kg_{wood}}$

The maximum steel temperature reaches θ_{max} = 422 °C for the R60 beam and θ_{max} = 398 °C for the R60 column. By comparing the maximum steel temperature θ_{max} with the critical temperature from chapter 4.2 one can verify that in both cases no collapse will occur for the design fire load.

Beam R30: $\theta_{max} = 422\ ° < \theta_{crit} = 602{,}5\ °C$

Column R30: $\theta_{max} = 398\ °C < \theta_{crit} = 713{,}8\ °C$

8.6 APPLICATION OF THE SIMPLIFIED NFSC-METHOD TO THE BUILDING ACCORDING TO THE EXISTING DESIGN

Global safety index: $\gamma_{q,f} = \gamma_{q,1} \cdot \gamma_{q,2} \cdot \gamma_{ni} = 1{,}4 \cdot 1{,}0 \cdot 0{,}72 = 1{,}0$

Compartment:	$\gamma_{q,1}$ =	1,4	$A = 80\ m \cdot 20\ m = 1600\ m^2$
Danger of activation:	$\gamma_{q,2}$ =	1,0	normal risk
Fire fighting	γ_{ni} =	$0{,}80 \cdot 0{,}90 = 0{,}72$	automatic detection system

Design fire load:

$\mathbf{q_{f,d} = \gamma_{q,f} \cdot q_{f,char} = 1{,}0 \cdot 570{,}0\ MJ/m^2 = 570\ MJ/m^2}$

$q_{f,d}$: design fire load

$q_{f,char}$ = 570 MJ/m² characteristic value of the fire load (80% fractile)

The one-zone fire simulation program BSBG [26] was used to calculate the time temperature curve with the following parameters:

Fire load density: $q_{d,\,fire} = 570\ MJ/m^2$

Max. RHR: $\dot{q}_{d,\,fire} = 320\ \frac{kW}{m^2}$

Fire spread: v = 0,5 m/min(in each direction starting from the middle of the room)

Combustion ratio: $5\ \frac{kg_{air}}{kg_{wood}}$

The maximum steel temperature was θ_{max} = 485 °C for the R30 beam and θ_{max} = 525 °C for the R30 column. By comparing the maximum steel temperature θ_{max} with the critical temperature from chapter 4.2 one can verify that in both cases no collapse will occur for the design fire load.

Beam R30: $\theta_{max} = 485\ °C < \theta_{crit} = 602{,}5\ °C$

Column R30: $\theta_{max} = 525\ °C < \theta_{crit} = 630{,}0\ °C$

9 CONCLUSIONS

The analysis of the structural fire safety level of the two design concepts for an existing office building in Langenthal Switzerland (code design R60, maximum size of the compartment ≤ 600 m^2; alternative design R30, maximum size of the compartment 1600 m^2, which was actually built) was performed with three different methods.

All three methods show an acceptable safety level for both design concepts with a slightly higher structural reliability of the code complying concept. However the probabilistic and the simplified natural fire safety concept concentrate only on the influence of active fire protection on the required structural fire resistance. Further benefits of active measures for life safety are not taken into consideration at present.

Nevertheless all three methods allow for new flexibility in fire safety design of buildings by recognising the interaction between active and structural fire safety measures. This can lead to considerable savings for steel and composite structures without reducing the fire safety level.

10 SYMBOLS

A: room area

A: cross-section area

A_m: surface area of the member per unit length

A_p: area of the inner surface of the fire protection material per unit length of the member

A_t: total area of the floor, walls and ceiling including all the openings that surround the fire compartment

A_v: area of the vertical openings

b: room width

b_w: width of the vertical opening

c_a: specific heat of steel

c_p: specific heat of the fire protection material

d_p: thickness of the fire protection material

E: modulus of elasticity

f_y: yield strength of steel at room temperature

G: self-weight

G_B: self-weight of the beam

$G_{B,tot}$: total self-weight of the whole beam

G_C: self-weight of the column

h: room height

h_{sill}: height of the sill

h_{sofit}: height of the sofit

h_w: height of the vertical opening

$\dot{h}_{net,c}$: convection proportion of the net heat flux per unit area

$\dot{h}_{net,d}$: design value of the net heat flux per unit area

$\dot{h}_{net,r}$: radiation proportion of the net heat flux per unit area

i: radius of gyration

I_y: moment of inertia

$k_{E,\theta}$: relative value for the slope of the linear elastic range

$k_{y,\theta}$: relative value for the effective yield strength

l: room length

l: span of the beam

m: mean

M_d: design moment for the beam

n:	building lifetime (50 years)
N:	imposed load
N_b:	imposed load of the beam
N_C:	imposed load of the column
O_f:	opening factor
p_1:	probability of fire occurrence for a certain occupancy per year and m^2
p_f:	structural failure probability from a fire free status (unconditional failure probability)
$p_{f,fi}$:	structural failure probability given a severe fire (conditional failure probability)
p_{FRI} :	probability that a starting fire turns to a flash-over or a fully engulfed
p_M:	failure probability of fire fighting measures
p_{target}:	target failure probability of a structural member
$\dot{q}_{d,\,fire}$:	rate of heat release
$q_{d,f}$:	design fire load
q_t:	fire load in relation to A_t
R:	resistance
S:	snow load
S_d:	design load of the column
S_d:	design value
S_k:	characteristic value
t:	thickness of steel
u:	Gumbel parameter
v:	fire spread velocity
V:	variation coefficient
x:	exponent $x \leq 1{,}0$ taking into account the compartment size
Z_y:	section modulus

$\overline{\lambda}_{0,c}$: non dimensional slenderness for end conditions in fire and room temperature

Γ:

α: Gumbel parameter

$\gamma_{g,fire}$: partial safety factor for the self-weight in case of fire

γ_g: partial safety factor for the self-weight

$\gamma_{M,fi}$: partial material safety factor in fire design

γ_{ni}: differentiation factor γ_{ni} – Influence of the active fire fighting measures

$\gamma_{q,1}$: differentiation factor γ_{q1} – Influence of the compartment area

$\gamma_{q,2}$: differentiation factor γ_{q2} – Influence of the risk of fire activation

$\gamma_{q,f}$: global safety factor

γ_Q: partial safety factor for the imposed load

γ_R: partial safety factor for the resistance

η: load level

κ: adaptation factor

ℓ_{cold}: buckling length at room temperature

ℓ_{fire}: buckling length in fire

λ_p: thermal conductivity of the fire protection material

$\mu_{0,c}$: degree of utilisation

θ_a: steel temperature

θ_{crit}: critical steel temperature

θ_g: gas temperature

θ_{max}: maximum steel temperature

ρ_a: density of steel

ρ_p: density of the fire protection material

σ: standard deviation

ψ: partial safety factor

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