European Commission

technical steel research

Steel structures

Valorisation project — Natural fire safety concept

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Contract No 7215-PP/042
1 July 1999 to 30 June 2000

Final report

Directorate-General for Research

2002

EUR 20349 EN

A great deal of additional information on the European Union is available on the Internet. It can be accessed through the Europa server (http://europa.eu.int).

Cataloguing data can be found at the end of this publication.

Luxembourg: Office for Official Publications of the European Communities, 2002

ISBN 92-894-3698-0

Printed in Belgium

PRINTED ON WHITE CHLORINE-FREE PAPER

NATURAL FIRE SAFETY CONCEPT FOR BUILDINGS
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SUMMARY

The objective of the research "Natural Fire Safety Concept" 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 sponsored by the ECSC started in June 1994 and ended in June 1998. It has been undertaken by 11 European partners and is co-ordinated by PROFILARBED-Research.

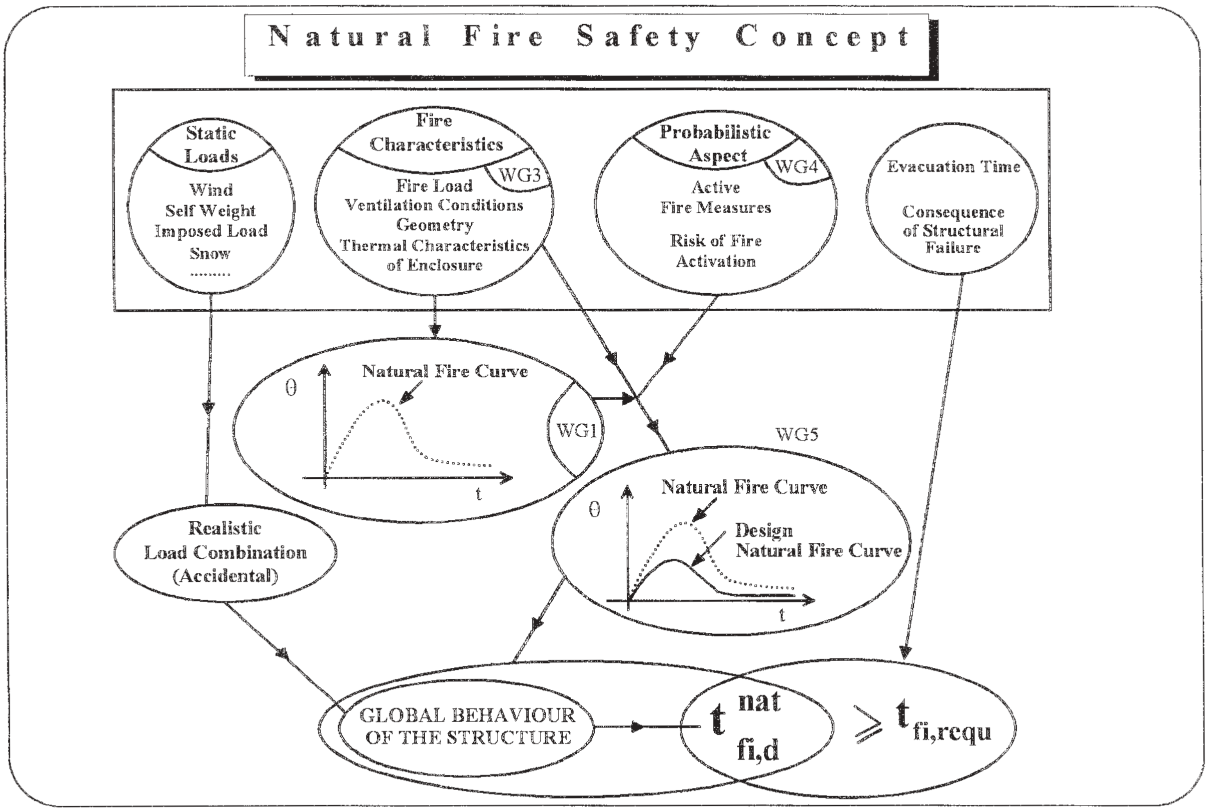


Figure A: General guidelines of the research " Natural Fire Safety Concept "

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
- 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
- deduces from the previous step, design values for the main parameters such as the fire load
- 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

- 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;
- 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 that are described in the final report of the research.

- 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).
- The Shopping mall in Rotterdam (The Netherlands).

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 spent in attempts to guarantee resistance of structures subjected, for instance, to two hours of a less realistic 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.

This book contains the essential points of the final report of the research "Natural Fire Safety Concept" where all the details are described.

All the working steps of the new approach have been submitted to an Advisory Committee comprising the national Fire Authorities of 8 European countries.

RÉSUMÉ

Afin de définir une approche plus réaliste d'analyse de la sécurité de la structure en cas d'incendie qui tient compte des mesures actives de lutte contre le feu et des caractéristiques réelles du développement d'un feu, la recherche intitulée "Natural Fire Safety Concept" financée par la CECA a été menée de juillet 94 à juin 98 par des organismes de 11 pays européens.

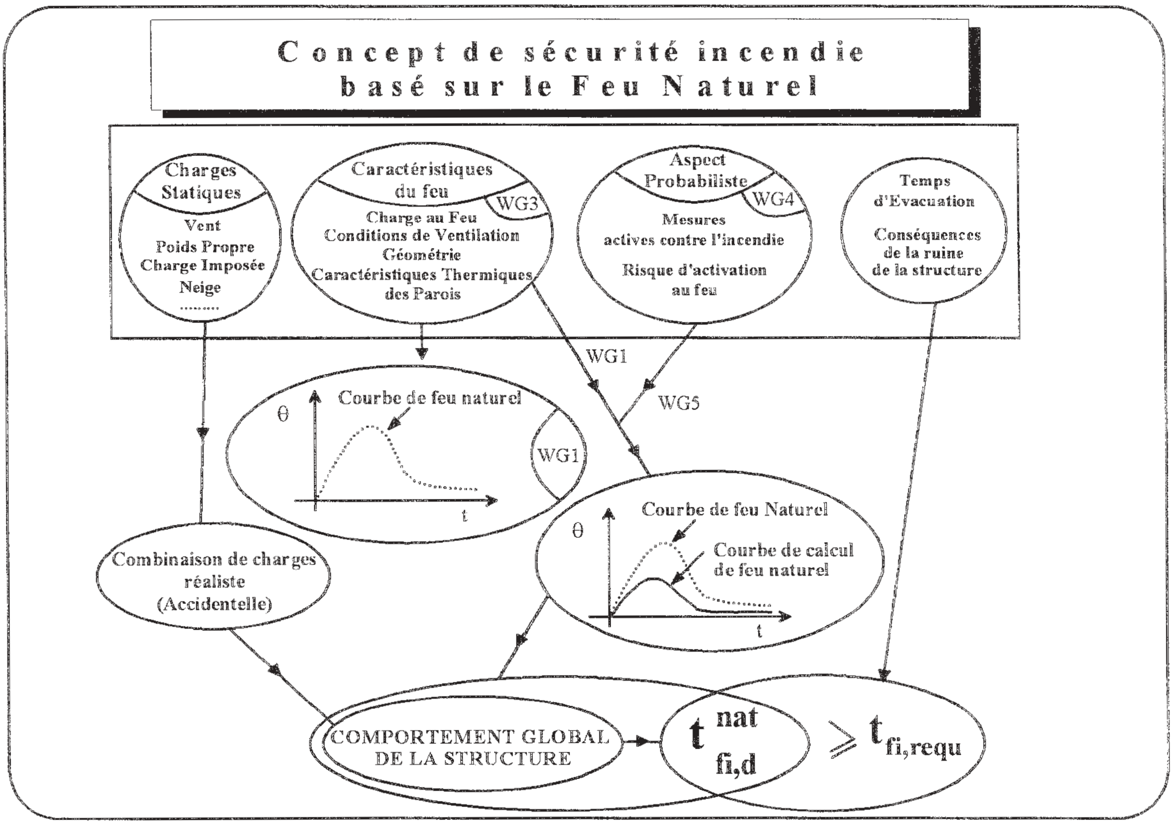


Figure A: Organigramme du rapport " Natural Fire Safety Concept "

Cette recherche a permis de mettre au point une procédure qui :

- prend en compte les caractéristiques du bâtiment déterminantes pour le développement du feu : scénario d'incendie, charge au feu, taux de pyrolyse, type de compartiment, condition de ventilation
- quantifie le risque de déclenchement d'un incendie et considère de ce fait l'influence des mesures actives et le type d'occupation du bâtiment; cette analyse du risque est basée sur des probabilités déduites de base de données de feux réels venant de Suisse, France, Finlande et du Royaume-Uni
- déduit de l'étape précédente des Valeurs de Calcul pour les paramètres principaux tels que la charge au feu
- détermine l'action thermique en fonction de la charge au feu de calcul qui tient compte implicitement du risque d'incendie et par conséquent des mesures actives de lutte contre le feu

- simule le comportement global de la structure sous l'effet de cette action thermique de calcul et des charges statiques en situation d'incendie;
- en déduit la durée de résistance $t_{fi,d}^{nat}$. Cette durée est très souvent égale à l'infini, ce qui signifie que la structure est capable de soutenir les charges qui lui sont appliquées depuis le début du feu jusqu'à son extinction;
- vérifie la sécurité de la structure en comparant la durée résistance $t_{fi,d}^{nat}$ à l'exigence t_{fi}^{requ} qui dépend du temps d'évacuation et des conséquences d'une ruine.

Ce nouveau concept a été appliqué à des projets réels de bâtiments et a permis de concevoir des bâtiments en acier sans surcroît de coût pour la sécurité au feu.

Citons les références suivantes qui sont décrites dans le rapport final de la recherche:

- Hall de Basket-ball à Pépinster (Belgique).
- Aéroport de Luxembourg (Grand-Duché de Luxembourg).
- Palais de Justice de Nantes (France).
- Bâtiment: Musée et Exposition à URBINO (Italie).
- Immeuble de Bureaux à Bilbao (Espagne).
- Bâtiment de Bureaux “Langenthal” (Suisse).
- Complexe Scolaire « Geesseknäppchen » à Luxembourg (Grand-Duché de Luxembourg).
- Centre Commercial à Rotterdam (Pays-Bas)

Vu les bénéfices financiers et une sécurité accrue car mieux ciblée qu'apporte cette nouvelle approche, les exemples de son utilisation devraient se multiplier. Au lieu de gaspiller de l'argent pour garantir une résistance au feu ISO de la structure de 2 heures, il est de loin préférable de mettre l'accent sur les mesures actives de lutte contre le feu pour la protection des personnes telles que détection, alarme, transmission automatique de l'alarme aux pompiers, désenfumage, cage d'escalier pressurisée, extinction automatique par sprinkleurs...

Si la sécurité des gens est assurée de façon optimale, la structure peut tirer parti de ces mesures prises pour sauvegarder les occupants et les coûts nécessaires pour assurer sa stabilité en cas d'incendie sont fortement réduits voire même inexistants dans certaines situations.

Le présent document de synthèse reprend les grandes lignes du rapport final de la recherche intitulée : "Natural Fire Safety Concept" et met en avant les principales règles définies pendant ces 4 années de recherche.

Toutes les phases de développement de cette nouvelle approche ont été soumises à un Comité d' Experts au Feu issus de 8 pays d'Europe.

SOMMARIO

L'obbiettivo della ricerca "Natural Fire Safety Concept" ("Concetto di Sicurezza basato sugli Incendi Naturali") è stabilire un approccio più realistico e credibile per l'analisi della sicurezza strutturale in caso di incendio che tiene conto delle misure di protezione attiva presenti e delle reali caratteristiche dell'incendio. La Ricerca Europea, sponsorizzata da ECSC, è iniziata nel giugno 1994 e si è conclusa nel dicembre 1998. Essa è stata condotta da 11 partner Europei e coordinata da ProfilARBED-Research.

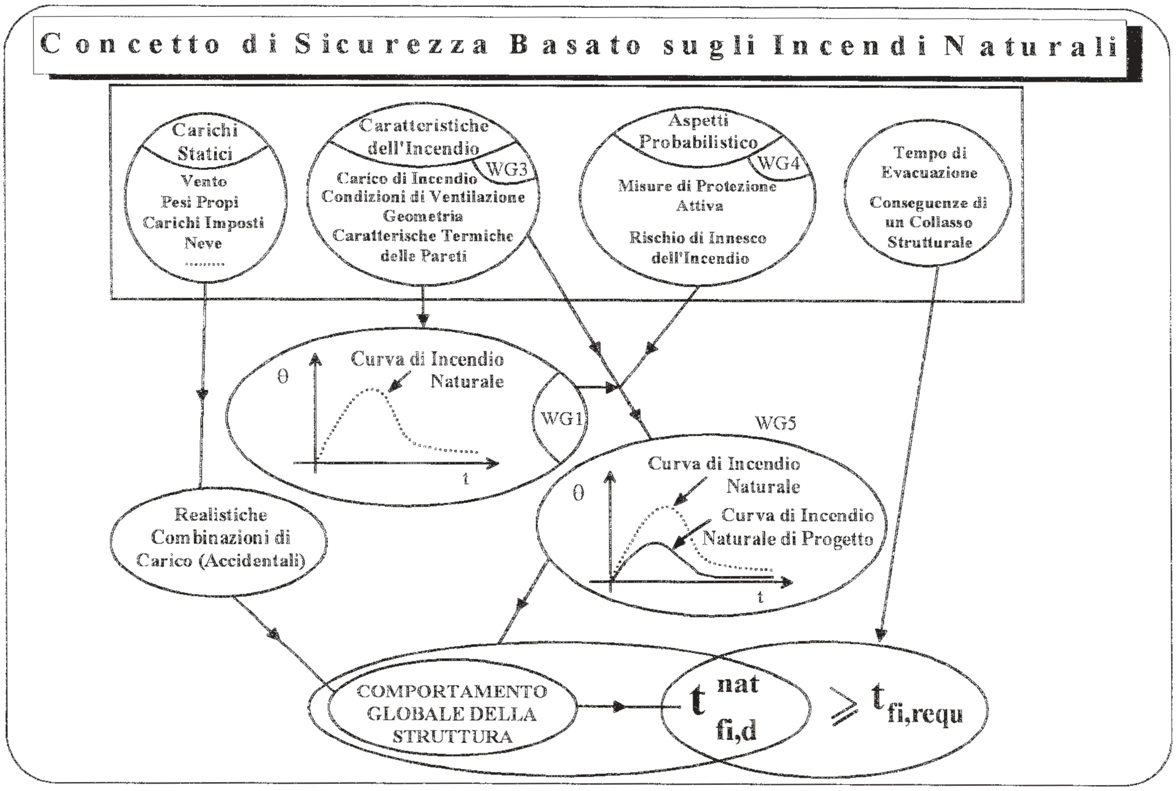


Figure A: Linee guida generali della ricerca "Concetto di Sicurezza Basato sugli Incendi Naturali"

Nella ricerca è stata sviluppata una procedura che:

- tiene conto delle caratteristiche dell'edificio che influenzano lo sviluppo dell'incendio: lo scenario dell'incendio, il carico di incendio, il tasso di pirolisi, le caratteristiche del compartimento e le condizioni di ventilazione
- quantifica il rischio di innesco dell'incendio e tiene conto delle misure di protezione attiva e del tipo di attività presenti; questa analisi del rischio è basata sulla probabilità dedotta da database di incendi reali verificatisi in Svizzera, Francia, Finlandia e Regno Unito
- deduce, sulla base dei punti precedenti, i valori di progetto dei parametri principali, come il carico di incendio

- determina la curva di riscaldamento di progetto in funzione del carico di incendio di progetto che tiene conto del rischio di incendio e quindi delle misure di protezione attiva
- simula il comportamento globale della struttura soggetta alla curva di riscaldamento di progetto ed ai carichi statici previsti in caso di incendio
- deduce il tempo di resistenza al fuoco $t^{nat}_{fi,d}$; questo può spesso essere infinito cosicché la struttura è capace di sopportare i carichi dall'inizio alla fine dell'incendio;
- verifica la sicurezza della struttura mediante la comparazione del tempo di resistenza al fuoco con il tempo richiesto che dipende sia dal tempo di evacuazione che dalle conseguenze nel caso di collasso strutturale.

Questo nuovo concetto è stato applicato ai seguenti progetti reali, descritti nel report finale della ricerca:

- Palazzetto dello Sport – Pallacanestro a Pepinster (Belgio)
- Aeroporto di Lussemburgo (Gran Ducato di Lussemburgo)
- Palazzo di Giustizia di Nantes (Francia)
- Museo e Sale Espositive a Urbino (Italia)
- Edificio per Uffici a Bilbao (Spagna)
- Edificio per Uffici "Langenthal" (Svizzera)
- Scuole "Geesseknäppchen" in Lussemburgo (Gran Ducato di Lussemburgo)
- Centro Commerciale a Rotterdam (Paesi Bassi)

Questo nuovo approccio porterà sia vantaggi economici che un migliore controllo della sicurezza. Così le sue applicazioni diventeranno più numerose. Meno investimenti saranno sprecati per garantire la resistenza di strutture soggette, per esempio, a due ore di un assolutamente non realistico incendio Standard. Invece, sarà evidente che è molto meglio individuare le misure attive che forniscono protezione per le persone, come sistemi di controllo, allarmi, trasmissione di allarme automatico ai Vigili del Fuoco, sistemi di evacuazione dei fumi e sprinklers.

Se la sicurezza delle persone è assicurata in modo ottimale, la struttura stessa potrà anche beneficiare di quelle misure che hanno lo scopo di garantire la sicurezza degli occupanti. Così, gli ulteriori costi necessari per garantire la sua stabilità in caso di incendio saranno sensibilmente ridotti e, in alcuni casi, anche ridotti a zero.

Questo libro contiene i punti essenziali del report finale della ricerca "Natural Fire Safety Concept" ("Concetto di Sicurezza basato sugli Incendi Naturali"), dove sono riportati in dettaglio tutti i risultati.

Tutti i contenuti del nuovo approccio sono stati sottoposti ad un Comitato Consultivo comprendente le Autorità Nazionali di prevenzione incendi di 8 paesi Europei.

SUMARIO

El objetivo del proyecto de investigación "Concepto de seguridad frente a incendio real" consiste en establecer un enfoque más realista y fiable para analizar la seguridad estructural en caso de incendio, considerando el efecto de las medidas activas de protección contra incendio y las características de los incendios reales. El proyecto, de ámbito europeo y financiado por la CECA (Comunidad Económica del Carbón y del Acero) comenzó en junio de 1994 y finalizó en Diciembre de 1998, y en él han participado 11 socios europeos liderados por PROFILARBED-Recherche.

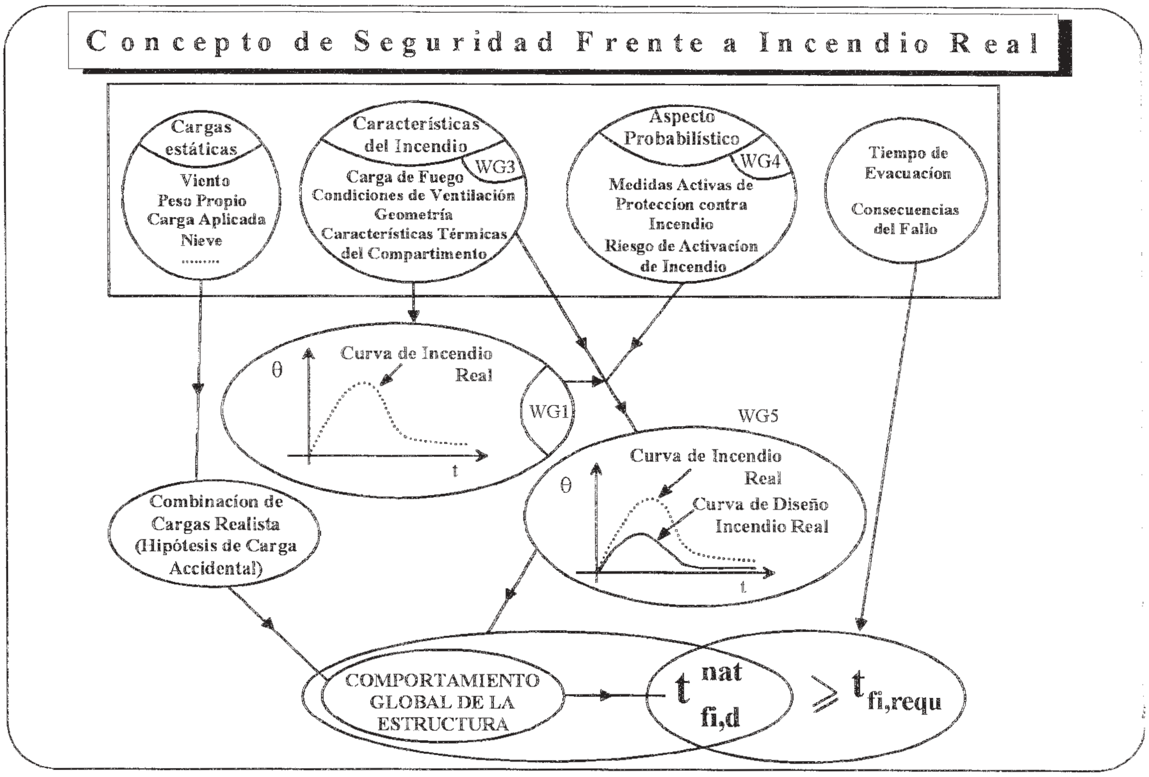


Figura A: Líneas generales de la investigación "Concepto de seguridad frente a incendio real"

En el marco del proyecto se ha desarrollado un procedimiento que:

- Tiene en cuenta las características del edificio relevantes desde el punto de vista de desarrollo de un incendio: escenario de incendio, carga de fuego, tasa de pirólisis, tipo de compartimento, y condiciones de ventilación
- Cuantifica el riesgo de que se inicie un incendio y considera la influencia de las medidas activas de protección contra incendio así como el tipo de ocupación; este análisis de riesgo se basa en valores de probabilidad deducidos de bases de datos existentes en Suiza, Francia, Finlandia y el Reino Unido
- Deduce valores de diseño para los parámetros fundamentales como la carga de fuego basándose en los resultados del paso anterior
- Determina la curva de calentamiento de diseño en función de la carga de fuego de diseño y teniendo en cuenta de forma implícita el riesgo de incendio y, consecuentemente, el efecto de las medidas activas de protección

- Simula el comportamiento global de la estructura sujeta a la curva de calentamiento de diseño y a la carga estática en caso de incendio
- Calcula el tiempo de resistencia a fuego $t_{fi,d}^{nat}$; éste puede ser en multitud de ocasiones infinito de forma tal que la estructura sea capaz de soportar las cargas desde el principio hasta el final del incendio
- Verifica la seguridad de la estructura comparando el tiempo resistente $t_{fi,d}^{nat}$ con el tiempo requerido en función del tiempo de evacuación y de las consecuencias del fallo

Este nuevo concepto ha sido aplicado a los siguientes proyectos reales que se describen en el informe final de la investigación:

- Un pabellón de baloncesto en Pepinster (Bélgica)
- El aeropuerto de Luxemburgo (Gran-Ducado de Luxemburgo)
- Palacio de justicia de Nantes (Francia)
- Museo y Palacio de Exposiciones en URBINO (Italia)
- Edificio de Oficinas en Madrid (España)
- Edificio de Oficinas "Langenthal" (Suiza).
- Escuela « Geesseknäppchen » en Luxemburgo (Gran-Ducado de Luxemburgo)
- Centro Comercial en Rotterdam (Países Bajos)

La aplicación del presente enfoque debería producir por un lado beneficios económicos, y por otro, mejores guías de seguridad frente a incendio. Consecuentemente, cabría esperar la implantación de su aplicación a casos reales. De esta forma se producirá una mejor gestión económica de la seguridad evitando, por ejemplo, requerimientos de estabilidad de dos horas ante el incendio normalizado ISO(UNE 23093) ya que quedan demostradas las ventajas de implantar medidas activas de protección contra incendios tales como elementos de detección, alarmas, conexión automática con los servicios de bomberos, rociadores y sistemas de evacuación de humos, que favorecen la seguridad de las personas.

Si se garantiza la seguridad de las personas de manera óptima, la propia estructura puede verse beneficiada por aquellas medidas orientadas a salvar a los ocupantes. En consecuencia, se reducen de manera importante los gastos adicionales orientados a garantizar la estabilidad de la estructura en situación de incendio.

Este documento contiene los puntos esenciales del informe final del proyecto "Concepto de Seguridad frente a incendio real" en el cual se describen todos los detalles.

Todos las etapas de trabajo de este nuevo enfoque han sido revisadas por un Comite de expertos compuesto por autoridades de los oganismos de incendio de 8 países europeos.

ZUSAMMENFASSUNG

Ziel des Forschungsprojekts „Brandsicherheitskonzept unter Berücksichtigung von Naturbrand“ ist eine realistischere und verläßlichere Einschätzung der Tragsicherheit im Brandfall, die eine aktive Brandbekämpfung und die Branddaten realer Brände berücksichtigt. Das durch die EGKS geförderte und im Juni 1994 begonnene europäische Forschungsprojekt wurde im Dezember 1998 abgeschlossen. An dem Projekt waren 11 europäische Partner beteiligt; die Federführung lag bei PROFILARBED-Research.

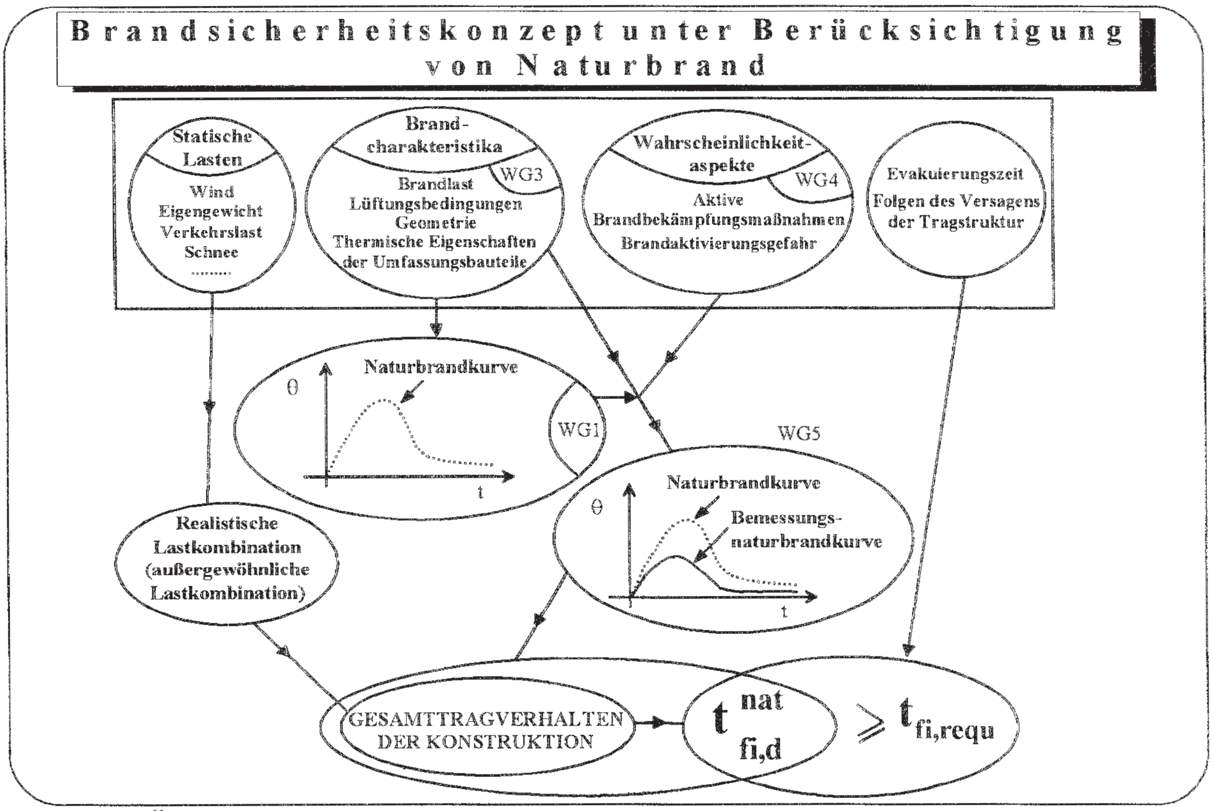


Abb. A: Überblick über das Forschungsprojekt „Brandsicherheitskonzept unter Berücksichtigung von Naturbrand“

Durch die Untersuchungen wurde ein Verfahren entwickelt, das

- die für die Brandentwicklung maßgeblichen spezifischen Bauwerkseigenschaften berücksichtigt: Brandszenario, Brandlast, Abbrandrate, Art des Brandraums und Be- und Entlüftungsbedingungen;
- das Risiko einer Brandentstehung quantifiziert und den Einfluß aktiver Brandbekämpfungsmaßnahmen sowie die Art der Bauwerksnutzung berücksichtigt; diese Risikoanalyse berücksichtigt Wahrscheinlichkeiten, die auf für Naturbrände in der Schweiz, Frankreich, Finnland und Großbritannien erstellten Datenbanken basiert;
- aus der o.g. Risikoanalyse Bemessungswerte für wesentliche Parameter, wie z.B. die Brandlast, ableitet;

- die rechnerische Bauteilerwärmung in Abhängigkeit von der rechnerischen Brandlast bestimmt, wobei das Risiko eines Brandes sowie Maßnahmen zur Brandbekämpfung berücksichtigt werden;
- das Gesamttragverhalten des Bauwerks bei statischer Belastung unter Bedingungen der rechnerischen Erwärmung im Brandfall simuliert;
- die Feuerwiderstandsdauer $t^{nat}_{fi,d}$ ermittelt; wenn die Tragfähigkeit des Bauwerks während der gesamten Brandeinwirkung erhalten bleibt, ist sie unbegrenzt,
- die Bauteilsicherheit durch Vergleich der Feuerwiderstandsdauer $t^{nat}_{fi,d}$ mit der notwendigen Evakuierungszeit nachweist oder den Nachweis der Gesamttragfähigkeit bei Versagen einzelner Gebäudeteile erbringt.

Dieses neue Konzept wurde auf reale Objekte angewandt, die im Abschlußbericht zum Forschungsprojekt näher beschrieben werden.

- Basketballhalle in Pepinster (Belgien)
- Flughafen Luxemburg (Großherzogtum Luxemburg)
- Gerichtsgebäude in Nantes (Frankreich)
- Museum und Ausstellungsräume in Urbino (Italien)
- Bürogebäude in Bilbao (Spanien)
- Bürogebäude „Langenthal" (Schweiz)
- „Geesseknäppchen"-Schule in Luxemburg (Großherzogtum Luxemburg)
- Einkaufszentrum in Rotterdam (Niederland)

Dieses Konzept verspricht sowohl finanzielle Vorteile als auch einen besseren Sicherheitsstandart, so dass zu erwarten steht, dass den genannten Anwendungsbeispielen bald weitere Umsetzungen folgen werden. Durch den Versuch, den Feuerwiderstand von Bauwerken z.B. für eine zweistündige Beanspruchung unter gänzlich unrealistischen ISO (oder ASTM)-Normbrandbedingungen zu garantieren werden unnötige Kosten verursacht. Als weitaus effektiver wird sich erweisen, die für einen Personenschutz erforderlichen Maßnahmen zur aktiven Brandbekämpfung, wie Feuermelder, Rauchmelder, automatische Übermittlung der Brandmeldung an Feuerwehreinsatzzentralen, Feuerlöscheinrichtungen, Rauchabzug und Sprinklerlöschanlagen, zu berücksichtigen.

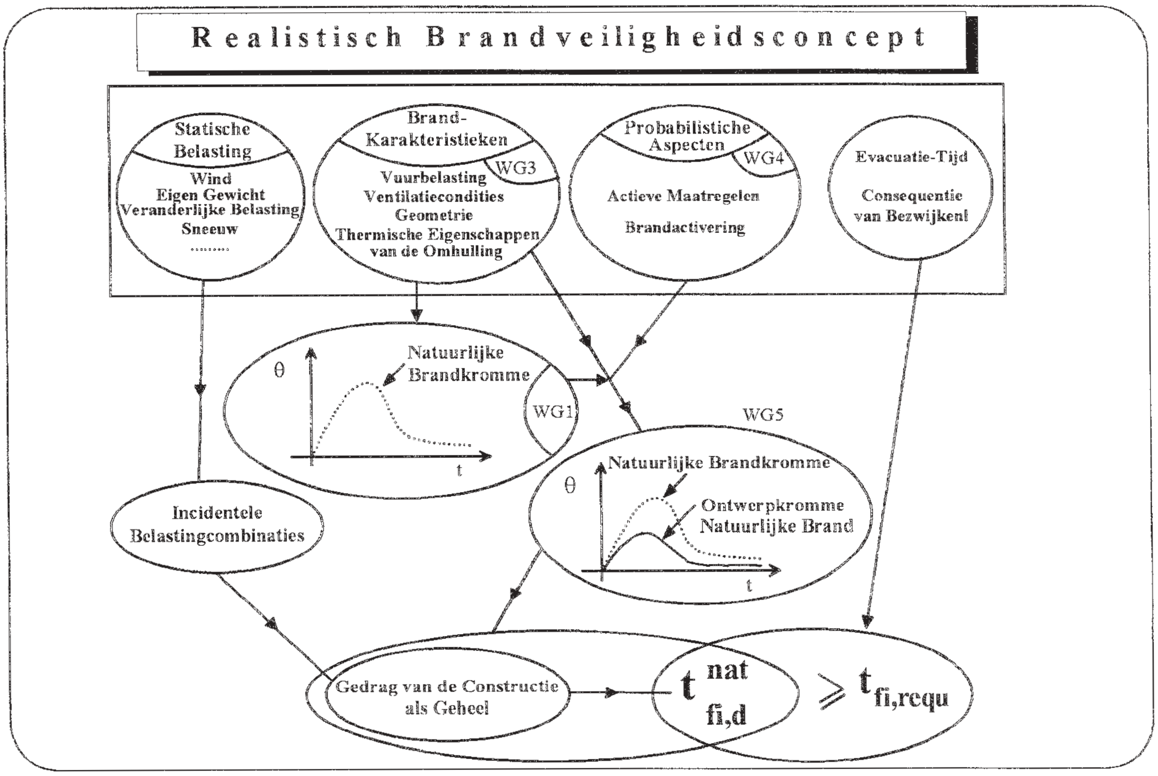
Optimaler Personenschutz bietet gleichzeitig Vorteile für das Bauwerk selbst, so dass die für die Gewährleistung der Tragfähigkeit im Brandfall zusätzlich aufzuwendenden Kosten erheblich gesenkt und unter Umständen vollständig vermieden werden können.

Die vorliegende Dokumentation enthält die wesentlichen Punkte des Abschlussberichts zum Forschungsprojekt „Brandsicherheitskonzept unter Berücksichtigung von Naturbrand".

Alle Arbeitsschritte der neuen Vorgebensweise wurden der Gutachterkomission der nationalen Feuerautoritäten von 8 Europäischen Ländern, unterbereitet.

SAMENVATTING

De doelstelling van het onderzoeksproject "Realistisch Brandveiligheidsconcept" is het ontwikkelen van een meer realistische en meer geloofwaardige benadering van de constructieve brandveiligheid, door uit te gaan brandomstandigheden zoals die zich in werkelijkheid voordoen en door het effect van actieve brandveiligheidsmaatregelen in de beschouwing te betrekken. Het project is financieel ondersteund door de Europese Gemeenschap voor Kolen en Staal (EGKS) en heeft geduurd van juni 1994 tot juni 1998. Het is uitgevoerd door 11 organisaties uit verschillende Europese landen en is gecoördineerd door PROFILARBED-Research.



Figuur A: Algemene opzet van het project " Realistisch Brandveiligheidsconcept"

In het project is een procedure ontwikkeld waarmee:

- de eigenschappen van het gebouw & inhoud die van invloed zijn op de ontwikkeling van de brand, in rekening kunnen worden gebracht; het betreft hier met name het aan te houden brandscenario, de vuurbelasting, de afbrandsnelheid, de functie en de afmetingen van het brandcompartiment en de ventilatiecondities;
- de kans op ontstaan van een ernstige brand wordt aangegeven, rekening houdend met het effect van actieve brandveiligheidmaatregelen en het gebruik van het gebouw; deze risicoanalyse is gebaseerd op realistische gegevens uit Zwitserland, Frankrijk, Finland en Engeland;
- stap voor stap ontwerpwaarden worden afgeleid voor de van belang zijnde ontwerpparameters (vuurbelasting, etc.);

- ontwerp-brandkrommen worden bepaald, afhankelijk van de ontwerpwaarde van de vuurbelasting; in deze ontwerpwaarde is o.m. de kans op ontstaan van de brand verwerkt en daarmee ook het effect van actieve maatregelen;
- het gedrag van de aan brand blootgestelde constructie wordt gesimuleerd, rekening houdend met o.m. de bij brand maatgevende statische belasting;
- de weerstand tegen brand $(t_{fi,d}^{nat})$ wordt bepaald; in die gevallen waarin de constructie in staat is gedurende de volledige duur van de brand de belasting te dragen, is deze weerstand onbepaald groot;
- de constructieve brandveiligheid wordt beoordeeld door de weerstand tegen brand $(t_{fi,d}^{nat})$ te vergelijken met de vereiste weerstand, welke afhankelijk is van de benodigde evacuatietijd en de consequenties van eventueel bezwijken van de constructie.

Het ontwikkelde brandveiligheidsconcept is toegepast op een aantal in de praktijk uitgevoerde projecten, zoals beschreven in eindrapport van het onderzoek:

- sporthal in Pepinister (België)
- terminal van het vliegveld van Luxemburg (Luxemburg)
- gerechtsgebouw in Nantes (Frankrijk)
- museum- en tentoonstellingsgebouw in Urbino (Italië)
- kantoorgebouw in Bilbao (Spanje)
- kantoorgebouw “Langenthal” (Zwitserland)
- schoolgebouw “Geesseknappchen” in Luxemburg (Luxemburg)
- winkelcentrum in Rotterdam (Nederland)

De nieuwe benadering leidt zowel tot een meer economisch ontwerp als tot een beter inzicht in de feitelijke veiligheid. Het verdient aanbeveling het aantal voorbeelden van toepassingen uit te breiden. Dan zal blijken dat minder geld zal worden besteed aan onrealistische, uitsluitend op de standaardbrandkromme gebaseerde eisen. Het zal duidelijk worden dat het – ter voorkoming van ongevallen - veelal beter is de nadruk te leggen op actieve maatregelen zoals detectie (met automatische doormelding naar de brandweer), rookafvoer en sprinklers.

Indien de veiligheid van de aanwezigen op optimale wijze is zeker gesteld, leidt dit ook tot positieve effecten voor het constructieve gedrag van het aan brand blootgestelde gebouw. Dit betekent dat bespaard kan worden op de kosten om aan de constructieve brandveiligheidseisen te voldoen. Onder omstandigheden zouden aparte maatregelen in dit verband zelfs achterwege kunnen blijven.

Deze publicatie bevat de belangrijkste uitkomsten van het onderzoeksproject “Natuurlijk Brandveiligheidsconcept”. Voor details wordt verwezen naar het eindrapport van het project.

De verschillende stappen in de voorgestelde ontwerpprocedure zijn besproken binnen een adviescomité waarin nationale brandweerautoriteiten uit 8 Europese landen waren vertegenwoordigd.

1 INTRODUCTION

In the sixties, a number of dramatic fires, such as the fire at the supermarket "Innovation" in Brussels which left more than 300 dead and the fire at the discotheque 'Le cinq Sept' in Saint-Laurent-du-Pont in France led to a lot of new regulations everywhere in Europe

Current regulations deal with a number of areas, including:

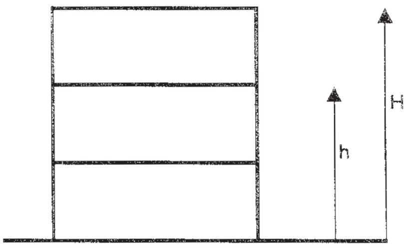
- Means of escape: standards specify requirements such as the number of emergency exits, the characteristics of the exit signs, the number of staircases and the width of the doors.
- Fire spread: including, "fire resistance" and "reaction to fire":
  - The compartments are limited by fire resistant walls and doors. There are clauses limiting the size of compartments and defining the minimum sill heights of windows to avoid fire spread from one floor to another.
  - The reaction to fire determines the contribution to fire development of the material within the compartment.
- The fire resistance of the structure: defined in terms of resistance periods, R30, 60, 90 or 120.
- The smoke and heat exhaust ventilation system.
- Active fire fighting measures such as hand extinguishers, smoke detectors, sprinklers.
- Access for the Fire Brigade.

Each country has defined its own regulations generally based on its own view of the problem. This means that these requirements have been based on historical considerations, experience, real fire lessons and mainly expert judgement. Even if the general context and general notions of fire safety are the same everywhere in Europe, the requirements are non-uniform. Table 1.1 gives the present structural requirements based on standard ISO-Fire (see ISO R834) for different types of buildings.

The main parameters defining the requirements are the height of the building and the occupancy of the building related to the number of occupants and type of activities. In Europe, regulations concerning fire resistance can be very different from one country to another. For example one can see the case of a single storey commercial centre for which no fire resistance (CH) up to 90 min (SP) ISO-Fire resistance are required, or the medium rise office building for which ISO-Fire resistance from 60 minutes (NL) to 120 minutes (FIN) are required.

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

Fire resistance requirements should be based on the parameters influencing fire growth and development. These include:

- Fire [probability of Fire occurrence, Fire spread, Fire duration, Fire load (amount and distribution), Severity of the Fire (Rate of Heat Release)]
- 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

The current regulations do not take adequate account of the influence of sprinklers in suppressing or extinguishing the fire. Table 1.1 shows that, except for very few cases, the present requirements are identical whether sprinklers are present or not.

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

The aim was to establish a more realistic and more credible approach to analyse structural safety in case of fire to include active fire fighting measures and real fire characteristics. Thus it is possible to define, for each compartment within a given building a "natural" fire curve.

Figure 1.1 shows a comparison between the "natural" fire curves for different configurations (compartment size, fire loads, walls insulation, combustible characteristics,...) and the standard ISO-Fire curve.

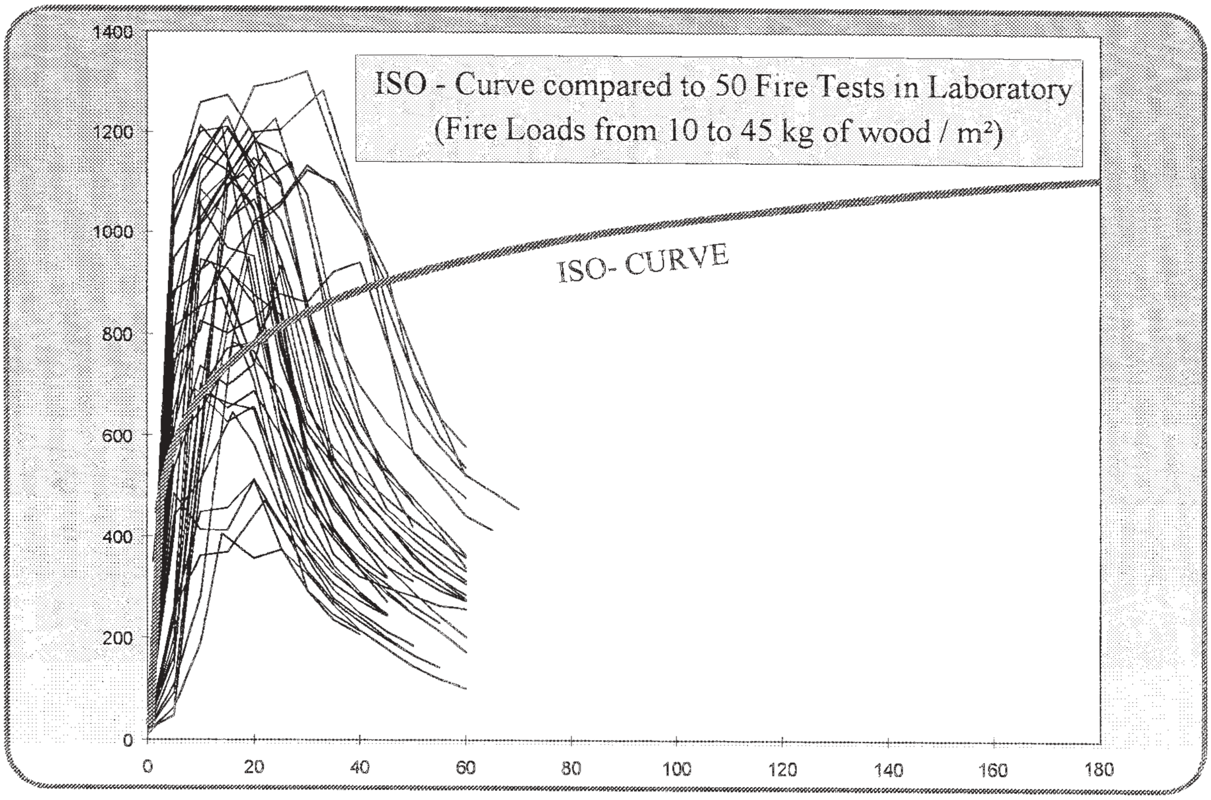


FIGURE 1.1: Temperature-time curves from natural fire and from ISO-Fire

This shows the difficulties to understand the behaviour of elements in case of real fires using data obtained according to the single ISO-Fire curve. A real fire has characteristics that are not taken into account in the standard ISO-Fire curve. The characteristics of a real fire are shown in Figure 1.2 and include:

- A smouldering phase: ignition and smouldering fire at very low temperature with a duration that is often difficult to estimate. This phase is not shown in Figure 1.2.
- A growing phase called pre-flashover (localised fire): the duration of this phase depends mainly on the characteristics of the compartment. The fire remains localised up to a possible flashover.
- A flashover: the flashover is a generalised fire. This phase is generally very short.
- A post flashover fire: this phase corresponds to a generalised fire for which the duration depends on the fire load and the ventilation.
- A decreasing phase: the fire begins to decrease until all the combustible materials have completely burnt.

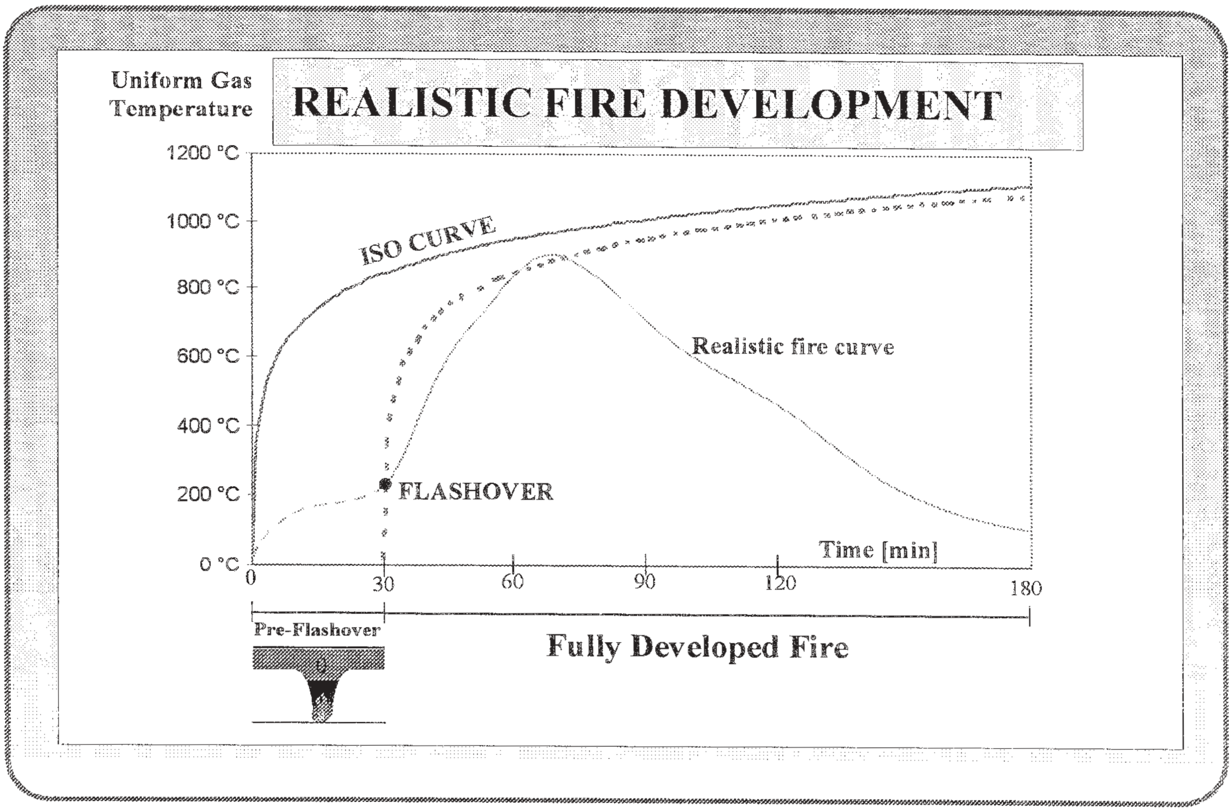


FIGURE 1.2: Natural fire phases

In order to develop a new global fire safety concept based on natural fire curves, it was necessary to define and evaluate the existing global safety concept (generally based on ISO-Fire curve) and the models for determining natural fire development.

Subsequently, a new methodology has been developed based on statistical, probabilistic and deterministic approaches and analysis. This method is applicable to all structural materials and buildings.

The development of this concept was co-ordinated during the four years of the research, by an **Advisory Committee** (see Chapter 9) composed of firemen, fire regulators and engineers from the 11 countries involved in the research.

This aim of the present report is to give the main data and the methodology for applying the global natural fire safety concept. The background of the method, of the models and of the statistics is given in the full report of the research 'Competitive steel building through natural fire safety concept' [1].

2 METHODOLOGY

2.1 GENERAL PRESENTATION

The determination of the fire development in a fire compartment requires knowledge of a large number of parameters. A number of these parameters are fixed by the characteristics of the building.

Nevertheless, the main characteristic, the "fire load" is generally a function of the activity and may not be a constant during the life of the building. The fire load can be defined as a statistical distribution. For structural design at ambient temperature, the mechanical loads such as self-weight, imposed load and wind are also defined by a statistical distribution.

Consequently, it was decided to determine the fire safety in a building using a probabilistic approach. In the global natural fire safety concept, the objective is defined by a target value of failure. The objective is not to change the safety level actually existing through the prescriptive codes but to obtain a realistic value.

The combination of active and passive measures can be used to reach an acceptable level of safety.

The general method of safety quantification is based on the method used for structural design at ambient temperature and defines a design fire load taking into account the probability of fire occurrence and the influence of active fire fighting measures.

The design fire load is then used in the fire calculations models to assess the structural fire behaviour. The present report gives the rules for assessing the fire behaviour of the structure. Models to determine the temperature within the compartment and in structural elements are described. From the temperature field in the structure, the structural fire behaviour can be studied with simple or advanced calculations models. A global structural fire behaviour has to be checked and fire structural design can be determined.

2.2 MEANS AND OBJECTIVES

2.2.1 PERFORMANCE TO ACHIEVE

The objective is to reach an acceptable safety level. This acceptable safety level can be defined by comparison to the other existing risks in life including the structural collapse of the building in normal conditions. The target probability to have a structural collapse in normal conditions is 7,23 10^{-5} per building life.
The objective is:

$$P_f \text{(probability of failure)} \leq P_t \text{ (target probability)}$$

According to the single definition of the objective, the safety level is mainly defined by the target probability. Two levels of calculation complexities are described and developed:

- Level 1: The design fire load is calculated in a simple way from a characteristic fire load multiplied by the different safety and weighing differentiation factors (based on fixed target failure probability of 7,23 10^{-5} per building life).
- Level 2: the global probabilistic approach is developed and described in order to apply it using any target probability that can be obtained from an improved statistical and risk approach.

As it is defined in the Eurocodes, the fire is an accidental action. A large statistical study has been realised in order to determine the probability to have a fire occurence. This ignition is a function of the activity of the building. A good correlation between statistics coming from different European countries has been found.

When the fire has started, a collapse can occur only if the fire reaches severe conditions. It is necessary to define the probability that the fire grows to a severe fire. In this phase, the active measures, the occupants and the firemen have an important role to play. It means that in a large number of cases, this fire will be stopped very quickly, and will never grow. According to statistics, the actions of active measures and fire brigade intervention considered in the building have been assessed to determine the probability to have a severe fire.

So according to the active (sprinkler, detection, ...) and passive (compartmentation) measures used in the building, the activity in the building and the fire brigade intervention, a design fire load is calculated from the target probability. This global safety concept is developed and detailed in the chapter 5.

2.2.2 FIRE DEVELOPMENT CALCULATION METHOD

Different levels of fire development calculation methods exist:

- simple models: mainly the parametric fires which can be used for pre-design calculation
- zone-models: these models take into account all the main parameters controlling the fire
- field models: too complex for use as a general design tool and should be limited to specific cases. Field models are the only tools valid for sophisticated geometry.

As a first step the research has analysed zone models: both one-zone and two-zone models. The assumptions of the one-zone model are related to a generalised fire with uniform temperature in the compartment while the two-zone models are related to a stratified smoke layer from a localised fire.

The main parameter of the fire development is the rate of heat release (RHR). This rate of heat release is a function of compartment size and activity and a function of time. As it was described in the first chapter, ignoring the smouldering phase, the fire is initially a localised fire in the pre-flashover phase. The beginning of this phase is characterised by a fire growth that has been quantified according to a t^2-fire assumption. This means that the rate of heat release is defined by a parabolic equation. The buildings are classified into 4 categories according to the fire-spread velocity: low, medium, fast and ultra-fast. The rate of heat release will reach a maximum value corresponding to a steady state defined by fuel or ventilation control conditions.

One of the assessments is to know the RHR evolution and to define whether the fire will grow to a flashover or will remain a localised fire.

A large number of zone-models exists in the world, the background of these models or the code source are often not available. It was therefore decided to develop, during this research, a one-zone model called Ozone. This one-zone model was then verified by a comparison with another existing one-zone model (NAT [32]), and validated by comparison with an over 100 experimental tests collected in a database.

When the conditions of flashover or generalised fire are not reached, a fire remains localised. In this condition, a two-zone model is used to estimate the general effect of the smoke layer. The local effect near the fire is also studied by empirical models developed in a previous research 'natural fire in large compartments' [20]. Hasemi [29] performed experimental investigations to determine the localised thermal actions from a fire, from which a simplified method was developed. The combination of both models allows the determination of the temperature field near and far away the fire.

The main result of the models is thermal actions to the structure.

2.2.3 STRUCTURAL FIRE BEHAVIOUR

According to this thermal action, the thermal transfer to the structural elements has to be calculated. The models of different levels can be used.

From the temperature field in the structure and from the combination of the mechanical loads in case of fire, the structural behaviour can be assessed with models also having different levels.

Simplified models using element/element calculations can be applied. Generally this model is based on the notion of critical temperature. If the heated temperature is below the critical temperature there is no failure and if the heated temperature is higher than the critical temperature there is failure. It is a 'pass or failure' criterion. The objective is then reached if the time to reach the failure is greater than the required natural fire exposure.

More sophisticated models, for example using finite element calculations, can be used. The results of the model are generally in terms of deformation during the whole fire duration. In some cases, the performance criteria (to measure at which level the objectives are fulfilled) can be given in terms of deformation. A knowledge of the structural fire behaviour allows for an assessment against a range of performance criteria in terms of limited deformation or structural damage. The choice of performance for design purposes will be dependent on the consequences of failure and the function of the building. For certain high-profile multi-storey buildings this may mean that no structural damage must take place during a fire.

The characteristics of these models will be developed in the chapter 7.

2.3 REQUIRED DATA

In order to apply this methodology, the characteristics of the building have to be known. This methodology is applied compartment by compartment. The compartment has to be defined in terms not only of the geometry, but also the thermal characteristics of the walls that are able to accumulate and to transfer a large part of the energy released by the fire, and the openings which allow the air exchange with the outside of the compartment. This will be the task of chapter 3.

Some rules and tables will be given in order to determine all these data.
In order to estimate the probability of the fire to grow to a severe fire, the active measures selected to be used in the building have to be known. These active measures will be defined as reduced probabilities for the level-2 method, or as a safety factor for the level-1 method.

3 CHARACTERISTICS OF THE FIRE COMPARTMENT

3.1 INTRODUCTION

In the "Natural Fire Safety" approach, the fire safety design is based on physically determined thermal actions. In contrast with 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 and realistic design fire scenarios is a crucial aspect of fire safety design. The assumptions made with regard to these factors have a major influence on the conditions in the compartment and have a 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. Only "credible worst case fire scenarios" will be studied. If the design fire scenarios are chosen, a number of fire models are available to calculate the thermal actions.

3.2 BOUNDARY ELEMENTS OF THE COMPARTMENT

In the Natural Fire Safety Concept, the fire development is described in the fire compartment. The assumption is that the fire will not spread to other compartments. Whether this is true, depends on the fire behaviour of the boundary constructions (floors, walls [including doors], etc.). It is necessary to understand this behaviour in order to assess their capability to function as fire barriers.

Such an assessment is complicated: a theoretical approach is – apart from some very simple and less practical situations – not feasible at present and experimental data mainly refer to standard fire conditions.

The following options are available:

- 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. However the number of fire tests needed may be 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. monolithic walls). For more complex wall constructions this approach is not feasible.

- Direct use of ISO-requirements
  National rules define fire compartments with ISO-fire resistance for walls, ceilings, doors and floors, depending on the use and the geometry of the building. In the scope of the "Direct use of ISO-requirements" it is assumed that a fire will not grow beyond the fire compartment. If the fire starts in an enclosure without ISO-fire rating boundaries, it could however be assumed that the fire will stay in this enclosure for 15 minutes.

The first two options can be used for a limited number of separating elements, and will lead to high costs. In practice, often the 3rd option has to be used due to the current lack of knowledge on the behaviour of compartments under real fires. However this needs to be solved in the future through research.

3.3 WALL: THERMAL CHARACTERISTICS

The heat loss from the compartment is an important factor for the temperature determination. Heat losses to the compartment boundaries occur by convection and radiation. The thermal properties of the walls have to be known.

The three main parameters characterising the thermal properties of a material are:

- heat capacity c_p
- density ρ
- conductivity λ

The conductivity and the heat capacity depend on temperature.

In zone and field models, the heat transfer through the walls is calculated with resolution of thermal transfer equations. The knowledge of these properties is necessary. When the dependence on temperature is not known, the characteristics at ambient temperature can be used. It is suggested to neglect the effect of water content.

In simplified models, only the thermal inertia, called b-factor, is used. The b-factor is determined by the following equation from the thermal properties:

$$b = \sqrt{\lambda \cdot \rho \cdot c_p}$$

In case of multi-material walls, it is suggested to deduce the b-factor from the following method:

- When a material (2) is insulated by a heavy material (1), so $b_1 < b_2$, the b-factor is the b-factor from the material 1: $b = b_1$.
- in the opposite, if $b_1 > b_2$, we can define a limit thickness for the material 1 equal to : $S_{1,\lim} = \sqrt{\frac{t_d \lambda_1}{c_1 \rho_1}}$ where t_d is the time of the fire up to the decrease phase.

Then the b-factor is determined by:

If $s_1 > s_{1,lim}$ then $b=b_1$

If $s_1 < s_{1,lim}$ then $b=\frac{s_1}{s_{1,lim}}b_1+\left(1-\frac{s_1}{s_{1,lim}}\right)b_2$

The following table gives the thermal characteristics of the most commonly used materials for different temperatures.

material	Temperature	λ (W/m/K)	ρ (kg/m^3)	c_p (J/kg°K)
Normal weight concrete	20	2	2300	900
	200	1,63	2300	1022
	500	1,21	2300	1164
	1000	0,83	2300	1289
Light weight concrete	20	1	1500	840
	200	0,875	1500	840
	500	0,6875	1500	840
	1000	0,5	1500	840
Steel	20	54	7850	425
	200	47	7850	530
	500	37	7850	667
	1000	27	7850	650
Gypsum insulating material	20	0,035	128	800
	200	0,06	128	900
	500	0,12	128	1050
	1000	0,27	128	1100
Sealing cement	20	0,0483	200	751
	250	0,0681	200	954
	500	0,1128	200	1052
	800	0,2016	200	1059
CaSi board	20	0,0685	450	748
	250	0,0786	450	956
	450	0,0951	450	1060
	1050	0,157	450	1440
Wood	20	0,1	450	1113
	250	0,1	450	1125
	450	0,1	450	1135
	1050	0,1	450	1164
Brick	20	1,04	2000	1113
	200	1,04	2000	1125
	500	1,18	2000	1135
	1000	1,41	2000	1164
Glas	20	0,78	2700	840

3.4 OPENING CHARACTERISTICS

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 relatively 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 O 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 as described below.

Concerning the opening factor O used in simplified models, it is defined according the following equation for a single vertical opening:

$$O = A_w \sqrt{H}$$

When several vertical openings have to be considered, the global area and an equivalent height have to be used. They are determined by:

$$\mathbf{A_W} = \sum \mathbf{A_{wi}}$$

$$H = \left[\frac{\sum A_{wi} \sqrt{H_i}}{\sum A_{wi}} \right]^2$$

where A_w is the opening area, H the opening height and i is relative to the opening n°i.

Concerning horizontal openings, few experimental data are available to give empirical equations for taking into account horizontal openings. The following methodology can be adopted to deduce the opening factor taking into account horizontal openings.

For a fire compartment containing horizontal openings, an equivalent opening factor can be calculated from the expression:

$$\left(A\sqrt{H}\right)_{eq} = f_k \left(A\sqrt{H}\right)_{vertical}$$

where

$\left(A\sqrt{H}\right)_{vertical}$ is the opening factor of vertical openings
and f_k a correction factor given by the following equations:

$$f_k = \left(1 + 0.03\left(Y - 1\right)\right) Y$$

with $Y = 2\dfrac{A_h\sqrt{h_1}}{A\sqrt{h}} + 1$

The different parameters are given by the Figure 3.1.

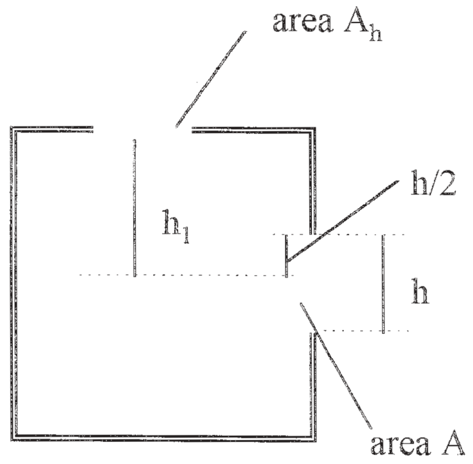


FIGURE 3.1: parameters defining the openings

3.5 MECHANICAL VENTILATION

The use of pressurisation and mechanical ventilation is more and more frequent. Their interaction with other fire parameters needs calculation models.

A study of **pressurisation** in case of fire is difficult. It is considered that the objective of pressurisation is always reached. It means an over-pressurised compartment will be smoke free, if the compartment boundaries keep their integrity.

The **mechanical ventilation** is also often used to smoke and heat exhaust ventilation system (SHEVS). Their effects on the fire development can be taken into account in advanced models. Nevertheless, in case of fully engulfed fire, the work of ventilators may stop: the fire-rating is generally defined for temperature less than 600°C. The mechanical ventilation has to be considered for localised fires. The ventilators, not defined as a SHEVS, use as air conditioning, will be ignored in fire development study. Usually the air conditioning is automatically stopped in case of fire alarm.

4 CHARACTERISTICS OF THE FIRE

It is the aim of this chapter to provide all the information needed by a designer when he faces a fire problem. The first data necessary to design a building against fire is to define the energy that is going to affect the structure. A way of knowing it would be to perform a real fire test in the building. This is uneconomic and besides would only provide information for one of the multiple fires that could happen in the building. Information from fire tests, existing models and fire dynamics have been combined so that a characterisation of the fire for different cases can be obtained .

4.1 FIRE LOAD

The first problem is to know which is the fire load to be considered in design. It is very rare that the fire load is known in a deterministic way. Generally it must be defined in a statistical way.

4.1.1 NATURE

The fire load Q in a fire compartment is defined as the total energy able to be released in case of fire. Part of the total energy will be used to heat the compartment (walls and internal gas), 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 4.1)
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 [m^2]

$H_{ui}.M_i$ 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 wood, a value of 17,5 MJ/kg is suggested for H_u leading to 14 MJ/kg for (mH_u).

Typical materials in buildings			
solids		**Plastics**	
wood	17,5	Polyurethane	23
Cellulosic materials (clothes, paper, cardboard, wool, silk, straw)	19	Polyurethane foam	26
wool	23	Polystyrène	40
Linoleum	20	Polyethylene	44
grease	41	Polyester	31
Cotton	20	Celluloid	19
Rubber tire	32	Melamine resin	18
Hydrocarbon			
gases		**Liquids**	
methane	50	Gasoline	44
acetylene	48	Oil	41
Butane - propane	46	Benzene	40
Ethanol	27	Benzyl alcohol	33
		Spirits	29
		Methanol	20
Others products			
Solids		**Plastics**	
Bitumen Asphalt	41	ABS	36
Leather	20	Acrylic	28
Paraffin wax	47	PVC	17
Coal, cork	30	Polycarbonate	29
Rubber isoprene	45	Epoxy	34

TABLE 4.1: Recommended net calorific value of combustible materials H_u (MJ/kg) for fire load calculation.

4.1.2 QUANTITY

The fire load density can be estimated by summing all the fire loads present in a building: it is a deterministic approach.

Some information is available on the fire load density for specific building types such as offices and schools. 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. These values of table 4.2 are derived from a compendium of commonly accepted values extracted from international documents [3, 30, 31].

	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 4.2: Data on fire load density for different buildings [MJ/m²] (fitting with a Gumbel type I distribution).

4.2 TYPE OF FIRE

Another question to be answered is what amount of the total fire load is going to burn in case of fire and how will this affect the Temperature-time curve occurring in the scenario.

Fires never (except for arson or explosion, which are not in the scope of the research) start at the same time in a whole fire compartment. They always start as a localized fire that, depending on a series of conditions, will develop to a major fire.

Main differences between a localised and a fully developed fire are listed below:

	Fire load	Gas temperature
Localised fire	Only a part of the compartment is in fire	Two zones (two temperature-time curves)
Fully developed fire	The fire load uniformly distributed in the whole compartment is in fire	One zone (one temperature-time curve)

In situations in which the whole compartment is involved in the fire, a uniform gas temperature is assumed. In a fully developed fire all fire load is burning so that the whole compartment is filled with smoke, combustion products and air that mix so well that the gas in the whole compartment can be considered homogeneous and represented by a single temperature.

In the scope of the research a method has been developed that allows for determining the Temperature-time curve(s) (T-t) to be used for the structural behaviour in case the fire is localised or fully developed. This will be described in details in chapter 6.

4.3 DESIGN FIRE

Once the fire load has been characterised it must be known at which rate the fire load will burn. This will lead to the RHR.

4.3.1 FUEL CONTROL AND VENTILATION CONTROL FIRES

The fire load defines the available energy but the gas temperature in a fire depends on the Rate of Heat Release. The same fire load burning very quickly or smouldering can lead to completely different gas temperature curves.

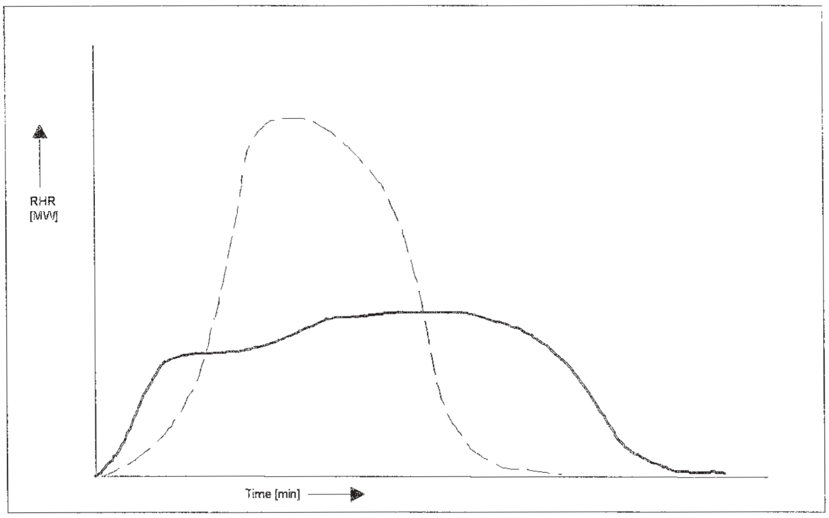


FIGURE 4.1: Two RHR curves corresponding to the same amount of fire load, as the surface beneath both curves is the same.

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 the maximum value without limitation of oxygen, 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 available oxygen limits the RHR and the fire is said to be **ventilation controlled**. Both ventilation and fuel-controlled fires can go through flashover.

This important phenomenon, flashover, 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 4.2, 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).

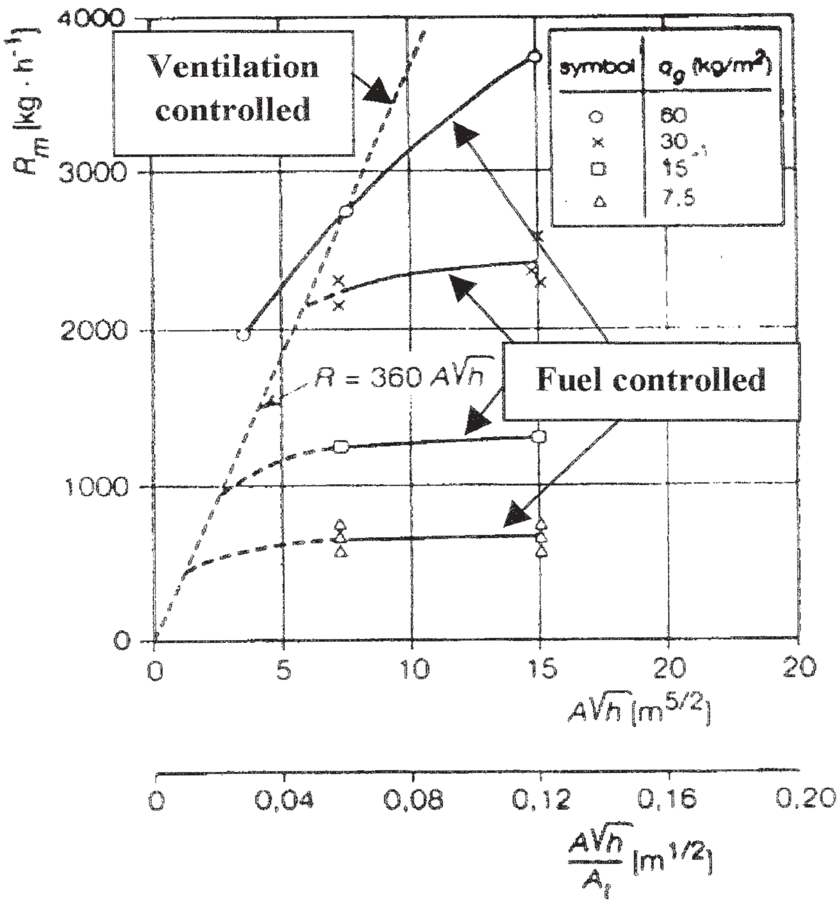


FIGURE 4.2: Mass rate for different fire load densities.

4.3.2 DESIGN RHR

The rise of the rate of heat release to the maximum value (see Figure 4.3) is given by :

$$\mathbf{RHR = (t / t_{\alpha})^2}$$

where:

RHR	=	Rate of heat release of the fire during growth phase	(MW)
t	=	time	(s)
t_{α}	=	time constant given in Table 4.3	(s)

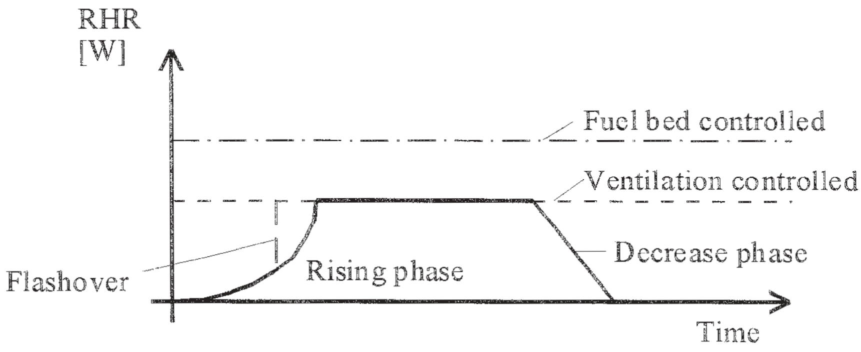


FIGURE 4.3: Rate of Heat Release vs. Time: Three phases are recognised: rise, stationary (post flashover) and decrease.

The fire growth parameter given in the code [3] varies according to building types and some guidance towards the classification and determination of this parameter is shown hereafter.

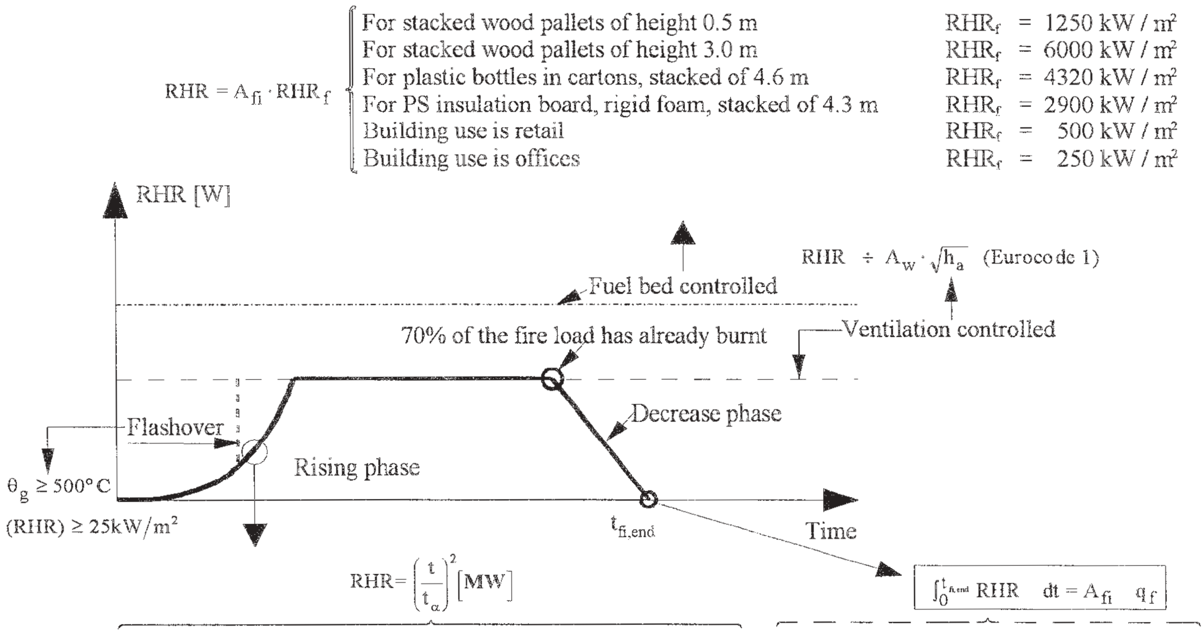
Occupancy/Activity	Fire growth rate	Time constant t_α(s)
Picture gallery	Slow	600
Storage building (low combustibility or few combustible materials)	Slow	600
Dwelling	Medium	300
Hotel room	Medium	300
Office	Medium	300
Storage building (cotton, polyester sprung mattress)	Medium	300
Shop	Fast	150
Storage 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 4.3: Fire Growth Rate t_α depending on the building occupancy

After the growing phase, the RHR curve follows an horizontal plateau with a maximum value of RHR corresponding to fuel bed (see figure 4.4) or ventilation controlled conditions.

There is no information about the decay phase in [2]. In [3] and [18] 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 has been consumed.

In the following Figure 4.4 the proposal for the RHR curve for the NFSC project is given. The curve includes the growing phase, steady state and the decay phase.



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

FIGURE 4.4: Design RHR curve

4.3.3 EXPERIMENTAL DATA

Another way to obtain the RHR curve is to make a test. Techniques for measuring heat release rates (except in a calorific bomb) 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, which is very difficult to do correctly. The oxygen depletion technique, however, has enabled these measurements to be made easily and with 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 [16]. This technique has been used and a database of test results established.

Different sources are available in the literature to extract data for the value of RHR [5,8,9,16].

The Hazard [9] 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, such as chairs, TV's and 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 a RHR curve. Argos [8] 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]. This has the same format as the Hazard database but contains more results. In this document one can find information not only on household objects but also objects such as various vehicle types.

CTICM in France has performed fire tests on new cars (fabricated in 1996) [21], on hotel rooms and on real furniture and measured the RHR. These experimental data are very interesting, because the majority of fire tests reported in the literature have been performed with wood cribs as fuel.

5 PROBABILISTIC ASPECT

5.1 INTRODUCTION

The probability that a fire breaks out in a swimming pool is obviously much lower than in a painting workshop. The probability that this fire spreads and leads to a fully engulfed compartment depends on the compartment area and on the active fire fighting measures such as sprinklers, automatic fire detection by smoke or heat, automatic alarm transmission to fire brigade and fire brigade intervention.

This ECSC research has enabled to gather **statistics** and to deduce the **probability** that:

- a fire starts
- the occupants fail to extinguish the fire
- the automatic active measures (sprinklers...) fail to extinguish the fire
- the fire brigade fail to extinguish the fire

The probability of successful intervention by the fire brigade depends mainly on the time to detect the fire (automatic fire detection by smoke or heat) and the time to reach the building (automatic transmission of the alarm and distance from fire brigade to building). For such active measures no explicit information is available in literature and, hence, assumptions have been made.

From those probabilities it is possible to deduce $\gamma_{q,f}$ **factor on the fire load** by a procedure based on the Annex A of **Eurocode 1 ENV 1991-1** [22] and **reliability calculations**. This procedure is summarized in chapter 5.4.

This factor γ_{qf} 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. The characteristic fire load $q_{f,k}$ has to be multiplied by $\gamma_{qf} = \gamma_{q1} \times \gamma_{q2} \times \gamma_{ni}$ to obtain the **design fire load** $q_{f,d}$.

The design fire load is then used by the "Natural Fire Models" tools (see following chapter 6) to calculate the design natural fire curve.

5.2 STATISTICS

This statistical study has been based on data from

- Switzerland : detailed information and analysis of all fires (± 40.000 fires) causing damage larger than 1.000.000 CHF in Berne from 1986 to 1995
- 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 the effects of sprinklers were summarised or collected from USA, Finland, Germany, France, Australia and UK [25].

The following statistics are mainly for dwellings, offices and industrial buildings. In chapter 5.4, offices have been adopted for developing the procedure. This procedure has been extended to other activities by the classification given in table 5.11.

5.3 PROBABILITIES

5.3.1 EVENT TREE ANALYSIS

An event tree (see Figure 5.1) may be established from fire start to describe fire growth, using recommended default values from Table 5.1.

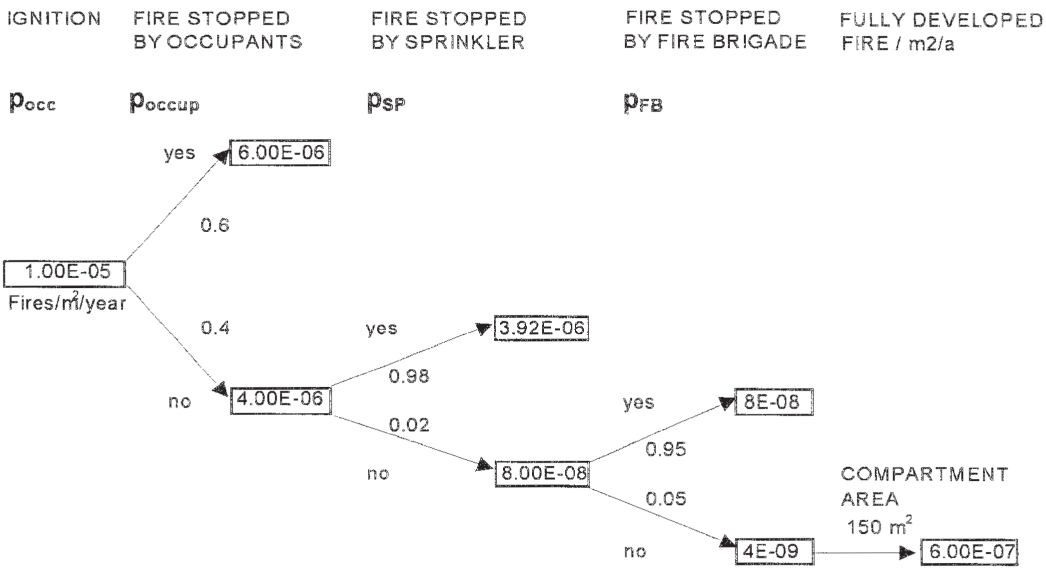


FIGURE 5.1: Example for an event tree for fire growth in an office with a compartment area of 150 m²

		Dwelling	Office	Industrial
Fire occurrence [1/(m².year)]	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}	see Table 5.5		
Fire stopped by standard fire brigade	p_{FB}	0,90 - 0,95	0,90 - 0,95	0,80 - 0,90

TABLE 5.1: Event tree factors

5.3.2 FIRE OCCURRENCE AND FIRE GROWTH

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

$$p_{fi} = p_1 \cdot p_2 \cdot p_3 \cdot A_{fi} \cdot p_4 \qquad (5.1)$$

with:

p_1 : probability of severe fire including the effect of occupants and public fire brigade (per m^2 of floor and per year)

p_2 : reduction factor depending on the fire brigade types and on the time between alarm and firemen intervention (p_2 is also the probability of failure of fire brigade in stopping the fire)

p_3 : reduction factor if automatic fire detection (by smoke or heat) and / or automatic transmission of the alarm are present

p_4 : reduction factor if sprinkler system is present (p_4 is also the probability of failure of sprinkler in stopping the fire)

A_{fi} : surface area of the fire compartment

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.

The influence of fire brigade types, time between alarm and firemen intervention, automatic detection and automatic alarm transmission (p_2, p_3) has not been considered in the Table 5.1, p_1 of Table 5.2 is in fact $p_{occ} * (1-p_{occup}) * (1-p_{FB})$.

For the application in the Natural Fire Safety Concept the following values are recommended for p_1, p_2, p_3 and p_4.

Occupancy/Activity	p_1 [$10^{-7}/(m^2 \cdot year)$]
Office	2 – 4
Dwelling	4 – 9
Industrial	5 – 10

TABLE 5.2: Frequency of fire start and growth to severe fire including standard public fire brigade

	Time between Alarm and Action of the FIREMEN		
p_2	$\leq$ 10'	10' < t $\leq$ 20'	20' < t $\leq$ 30'
Type of FIREMEN			
Professional	0,05	0,1	0,2
Not-Professional	0,1	0,2	1

TABLE 5.3 : Reduction factor depending on the fire brigade type and on the time between alarm and firemen intervention

Active Measures	p_3
Detection by smoke	0,0625
Detection by Heat	0,25
Automatic Alarm transmission to Fire Brigade	0,25

TABLE 5.4 : Reduction factor for automatic fire detection (by smoke or heat) and automatic transmission of the alarm

Type of sprinkler	p_4
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 5.5: Reduction factor for sprinkler system

5.4 PROCEDURE

5.4.1 DETERMINATION OF THE DESIGN VALUES OF ACTIONS AND RESISTANCES - SAFETY FACTOR γ IN THE EUROCODES - PRINCIPLE FOR NORMAL CONDITIONS OF USE

The resistance R and the Action S are according to statistical distributions, which are defined by the standard deviations (σ_S,σ_R) and the means (m_S, m_R). To ensure a sufficient safety, it is necessary that the failure (S > R) occurs only with a very low probability p_f represented given by the hatched area (see Figure 5.2). This area can be measured by the safety index β.

The Eurocodes in normal conditions require a maximum failure probability p_t of $7{,}23.10^{-5}$ for the building life, which corresponds to a safety index β_t of 3,8.

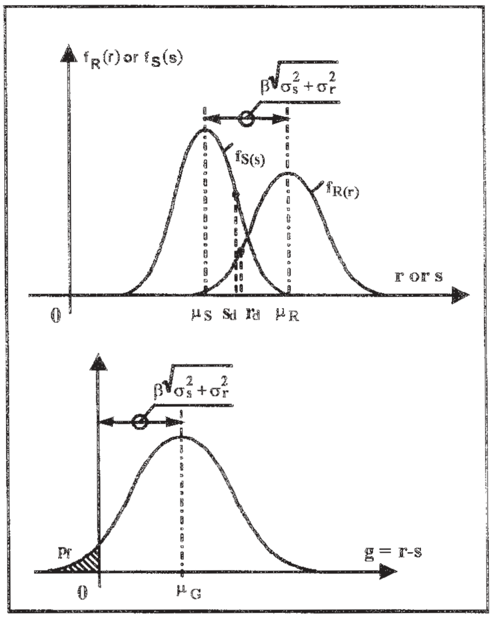


FIGURE 5.2

$$p_f \leq p_t \,(=7{,}23.10^{-5}) \rightarrow \beta > \beta_t \,(=3{,}8)$$

$$m_R - m_S \geq \beta \sqrt{\sigma_S^2 - \sigma_R^2} = \beta \frac{\sigma_S^2 - \sigma_R^2}{\sqrt{\sigma_S^2 - \sigma_R^2}}$$

$$\Rightarrow \overbrace{m_R - \frac{\sigma_R}{\sqrt{\sigma_S^2 - \sigma_R^2}} \beta \sigma_R}^{r_d} \geq \overbrace{m_S - \frac{\sigma_S}{\sqrt{\sigma_S^2 - \sigma_R^2}} \beta \sigma_S}^{s_d}$$

$$\Rightarrow r_d \geq s_d$$

$$If \; \frac{\sigma_R}{\sqrt{\sigma_S^2 - \sigma_R^2}} = 0{,}8 \; and \; \frac{\sigma_S}{\sqrt{\sigma_S^2 - \sigma_R^2}} = -0{,}7$$

$$\Rightarrow s_d = Design\,Value = m_S + 0{,}7\,\beta\,\sigma_S$$

$$\Rightarrow r_d = Design\,Value = m_R - 0{,}8\,\beta\,\sigma_R$$

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, of rebars,...)

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:

$$\alpha_R = \frac{\sigma_R}{\sqrt{\sigma_R^2 + \sigma_S^2}} = 0{,}8 \text{ for the resistance.} \qquad (5.2)$$

$$\alpha_S = \frac{\sigma_S}{\sqrt{\sigma_R^2 + \sigma_S^2}} = (-0{,}7) \text{ for the main action and } (-0{,}28) \text{ for the secondary action} \qquad (5.3)$$

By considering constant values for the weighing factors $\alpha_{s,i}$; the design values $s_{d,i}$ for actions can be defined without referring to the resistance, as these design values depend only on the safety index β, on the mean and the standard deviation of the corresponding statistical distribution and, of course, on the type of the distribution (see formulae of Figure 5.2 [22]).

This design values $s_{d,i}$ of the actions are thus the values of the actions which have to be considered in order to obtain the required safety. If β is equal to 3,8 as in the Eurocodes, 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 :

$$\gamma = \frac{s_d}{s_k} \qquad (5.4)$$

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 [2,28].

Hereafter the calculation of the γ_a of 1,1 for structural steel is given as an example.

- $\beta = 3{,}8$; $\alpha_a = 0{,}8$
- Statistical law : Lognormal
- Variation coefficients $\left(= \frac{\sigma}{m}\right)$:

  V_R = variation coefficient for the Design Value = $\sqrt{V_G^2 + V_m^2 + V_f^2} = 0{,}052$
  V_m = variation coefficient for Model uncertainty = 0,03
  V_G = variation coefficient for Geometry of element = 0,03
  V_f = variation coefficient or mechanical 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 : $\gamma_a = \frac{X_k}{X_d} = \exp(0{,}8\, \beta V_R - k\, V_f)$
  $= \exp(0{,}8 \,.\, 3{,}8 \,.\, 0{,}052 - 1{,}645 \,.\, 0{,}03)$
  $= 1{,}11$

5.4.2 TARGET VALUE

The assumption of a **target failure probability p_t of $7{,}23.10^{-5}$ per building life ($1{,}3.10^{-6}$ per year)** is defined in ENV 1991-1 [22].

That 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. In fact, the required safety in case of fire could be differentiated . This idea has been developed in the final report of the research (chapter 2.8 of the Annex B of WG5 part), where it is proposed to use a target failure probability p_t [1/year] depending on the people evacuation :

$p_t = 1{,}3 \,.\, 10^{-4}$ for normal evacuation p_t [1/year]
$p_t = 1{,}3 \,.\, 10^{-5}$ for difficult evacuation (hospitals, etc.)
$p_t = 1{,}3 \,.\, 10^{-6}$ for no possible evacuation (f.i. high rise building).

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 [22] accepted by everybody whereas discussions should be needed to convince the Authorities to adopt lower new target values.

5.4.3 FIRE DESIGN AND CONDITIONAL PROBABILITY

The Annex A of ENV 1991-1 [22], which describes the semi-probabilistic concept leading to the **design** values for the actions and for the material properties, has been extended to the structural fire resistance.

At room temperature, the safety factors for the actions $\gamma_{S,i}$ and the material properties $\gamma_{R,i}$ have been deduced by a semi-probabilistic approach which assumes implicitly that the failure probability of the structure p_f is lower than a target failure probability p_t of $7{,}23.10^{-5}$ per working life of the building, which is equivalent to a safety factor β of 3,8:

$$p_f \text{ (failure probability)} \leq p_t \text{ (target probability)} \qquad (5.5)$$

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 the structure only with a certain probability p_{fi}, p_{fi} being the product of p_{start} (probability that a fire starts) and p_{spread} (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 (5.5) becomes:

$p_{f,fi}$ (failure probability in case of fire) * p_{fi} (probability of fire) $\leq p_t$ (target probability).
which can be written:

- $p_{f,fi} \leq (p_t/p_{fi})$
- $p_{f,fi} \leq p_{t,fi}$ (5.6)

Whereas the target value p_t of $7{,}23 \,.\, 10^{-5}$ leads to the constant safety index β_t at room temperature, there is not in case of fire a fixed value of the safety index (called $\beta_{fi,t}$ in case of fire) because the target value $p_{t,fi}$ depends through equation (5.6) on the probability of fire p_{fi}. Knowing $\beta_{fi,t}$, the design value of the fire load can be deduced as explained hereafter.

5.4.4 DESIGN FIRE LOAD AND GLOBAL γ FACTOR

Reliability calculations (see chapter 7.4 of [23]) have showed that the weighing factor for the main action at room temperature is strongly reduced in case of fire and may therefore be considered as a secondary action whereas the fire load becomes the main action.

Moreover these calculations have pointed out that the assumption of the weighing factor of (-0,7) for the main action has to be modified and that a value of **(-0,9)** should be chosen for α_{qf}.

According to the fire load densities given in the U.K. document "The Application of Fire Safety Engineering Principles to the Safety in Buildings" [26] and Prof. Fontana's analysis [27], the data of fire loads fit well into a Gumbel type I distribution. A variation coefficient V_{qf} of 0,3 has been chosen [24].

As proposed in [28], a safety factor for the model for calculating the action effect γ_{sD} **=1,05** has been considered.

According to [22], the design value (see variable loads) for the Gumbel distribution is given by:

$$q_{f,d} = \gamma_{sD}\, m_{qf} \left\{ 1 - \frac{\sqrt{6}}{\pi} V_{qf} \left[0{,}577 + ln\left(- ln\, \phi\left(-0{,}9\, \beta_{fi,t} \right) \right) \right] \right\} \tag{5.7}$$

with m_{qf} the mean value of the fire load and ϕ the distribution function of the normal distribution

By choosing a characteristic value $q_{f,k}$ of **80 % fractile** (see Annex D of ENV1991-1-2 [2] and [24]), the factor γ_{qf} becomes:

$$\gamma_{qf} = \frac{q_{f,d}}{q_{f,k}} = 1{,}05 \frac{\left\{ 1 - \frac{\sqrt{6}}{\pi} V_{qf} \left[0{,}577 + \ln\left(- \ln \phi\left(-0{,}9\, \beta_{fi,t} \right) \right) \right] \right\}}{\left\{ 1 - \frac{\sqrt{6}}{\pi} V_{qf} \left[0{,}577 + \ln\left(- \ln 0{,}8 \right) \right] \right\}} \tag{5.8}$$

$$= 2{,}38 \text{ for } \beta = 3{,}8 \text{ and } 0{,}82 \text{ for } \beta = 0$$

The evolution of γ_{qf} as a function of $\beta_{fi,t}$ is given by the Figure 5.3.

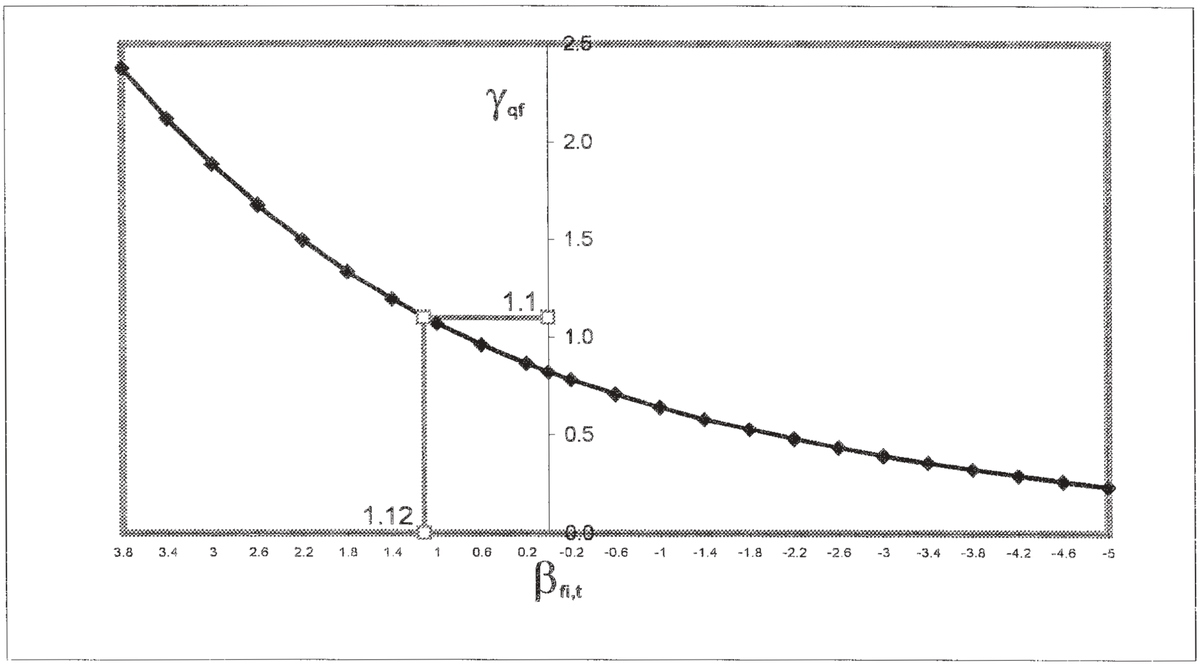


FIGURE 5.3 : Safety factor γ_{qf} as a function of β_{fi}

The safety index $\beta_{fi,t}$ can be calculated from the probabilty of severe fire p_{fi} by the following formula :

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

ϕ^{-1} is the inverse of the cumulative Standard Normal Distribution

The Figure 5.3 enables then to deduce the factor γ_{qf} for the fire load.

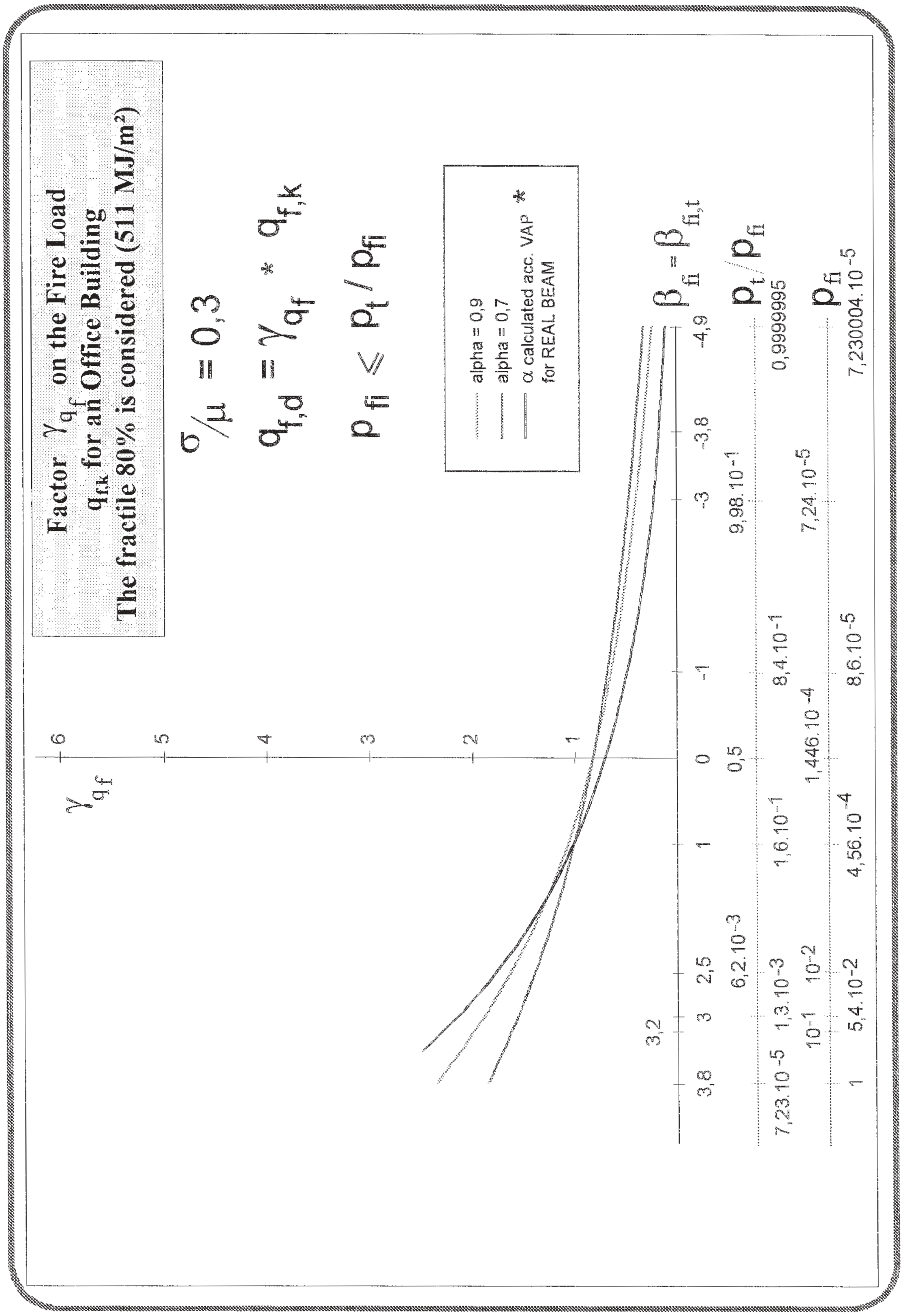
The following figure points out that the γ_{qf} obtained by using the simplified assumption $\alpha = (-0{,}9)$ instead of real reliability calculations is a reasonable assumption in the range relevant for fire design ($-\infty < \beta_{fi} < 2{,}5$).

This global procedure which implies

- to determine the probability to have a severe fire p_{fi}
- to calculate (p_t/p_{fi})
- to deduce the target reliability index $\beta_{fi,t}$
- to obtain the factor γ_{qf}

is given on tables 5.6 to 5.9 for the office buildings ($p_{fi} = 4 \,.\, 10^{-7} \times 55 = 2{,}2\ 10^{-5}$ per building life) with different combination of active fire safety measures.

This approach has been differentiated by splitting the factor γ_{qf} into 3 coefficients γ_{q1}, γ_{q2} and γ_{ni} to consider the influence on p_{fi} of respectively the compartment size, the risk of fire activation and the active fire fighting measures.



* reliability calculations. VAP Sofware Version 1.6 - Institute of Structural Engineering IBK, ETH Zürich.

FIGURE 5.4

Afi [m2]	Pfi	Sprinkler	Sprinkler 1Wat. Suply	Sprinkler 2 Wat. Suply	Detect. by heat	Detect. By smoke	Work Firemen	Off Site Firemen	Off Site Firemen Detect. by heat	Off Site Firemen Detect. By smoke	Off Site Firemen Detect. by heat Autom. Transm.	Off Site Firemen Detect. By smoke Autom. Transm.	Sprinkler Off Site Firemen Detect. by heat	Sprinkler Off Site Firemen Detect. By smoke	Sprinkler Off Site Firemen Detect. by heat Autom. Transm.	Sprinkler Off Site Firemen Detect. By smoke Autom. Transm.
Probability of failure of the Active measures		0,02	0,02 0,5	0,02 0,25	0,25	0,0625	0,02	0,1	0,1 0,25	0,1 0,0625	0,1 0,25 0,25	0,1 0,0625 0,25	0,02 0,1 0,25	0,02 0,1 0,0625	0,02 0,1 0,25 0,25	0,02 0,1 0,0625 0,25
→		0,02	0,01	0,005	0,25	0,0625	0,02	0,1	0,025	0,00625	0,00625	0,0015625	0,0005	0,000125	0,000125	0,00003125
1	2,20E-05	4,40E-07	2,20E-07	1,10E-07	5,50E-06	1,38E-06	4,40E-07	2,20E-06	5,50E-07	1,38E-07	1,38E-07	3,44E-08	1,10E-08	2,75E-09	2,75E-09	6,88E-10
25	5,50E-04	1,10E-05	5,50E-06	2,75E-06	1,38E-04	3,44E-05	1,10E-05	5,50E-05	1,38E-05	3,44E-06	3,44E-06	8,59E-07	2,75E-07	6,88E-08	6,88E-08	1,72E-08
50	1,10E-03	2,20E-05	1,10E-05	5,50E-06	2,75E-04	6,88E-05	2,20E-05	1,10E-04	2,75E-05	6,88E-06	6,88E-06	1,72E-06	5,50E-07	1,38E-07	1,38E-07	3,44E-08
75	1,65E-03	3,30E-05	1,65E-05	8,25E-06	4,13E-04	1,03E-04	3,30E-05	1,65E-04	4,13E-05	1,03E-05	1,03E-05	2,58E-06	8,25E-07	2,06E-07	2,06E-07	5,16E-08
100	2,20E-03	4,40E-05	2,20E-05	1,10E-05	5,50E-04	1,38E-04	4,40E-05	2,20E-04	5,50E-05	1,38E-05	1,38E-05	3,44E-06	1,10E-06	2,75E-07	2,75E-07	6,88E-08
125	2,75E-03	5,50E-05	2,75E-05	1,38E-05	6,88E-04	1,72E-04	5,50E-05	2,75E-04	6,88E-05	1,72E-05	1,72E-05	4,30E-06	1,38E-06	3,44E-07	3,44E-07	8,59E-08
150	3,30E-03	6,60E-05	3,30E-05	1,65E-05	8,25E-04	2,06E-04	6,60E-05	3,30E-04	8,25E-05	2,06E-05	2,06E-05	5,16E-06	1,65E-06	4,13E-07	4,13E-07	1,03E-07
175	3,85E-03	7,70E-05	3,85E-05	1,93E-05	9,63E-04	2,41E-04	7,70E-05	3,85E-04	9,63E-05	2,41E-05	2,41E-05	6,02E-06	1,93E-06	4,81E-07	4,81E-07	1,20E-07
200	4,40E-03	8,80E-05	4,40E-05	2,20E-05	1,10E-03	2,75E-04	8,80E-05	4,40E-04	1,10E-04	2,75E-05	2,75E-05	6,88E-06	2,20E-06	5,50E-07	5,50E-07	1,38E-07
225	4,95E-03	9,90E-05	4,95E-05	2,48E-05	1,24E-03	3,09E-04	9,90E-05	4,95E-04	1,24E-04	3,09E-05	3,09E-05	7,73E-06	2,48E-06	6,19E-07	6,19E-07	1,55E-07
250	5,50E-03	1,10E-04	5,50E-05	2,75E-05	1,38E-03	3,44E-04	1,10E-04	5,50E-04	1,38E-04	3,44E-05	3,44E-05	8,59E-06	2,75E-06	6,88E-07	6,88E-07	1,72E-07
275	6,05E-03	1,21E-04	6,05E-05	3,03E-05	1,51E-03	3,78E-04	1,21E-04	6,05E-04	1,51E-04	3,78E-05	3,78E-05	9,45E-06	3,03E-06	7,56E-07	7,56E-07	1,89E-07
300	6,60E-03	1,32E-04	6,60E-05	3,30E-05	1,65E-03	4,13E-04	1,32E-04	6,60E-04	1,65E-04	4,13E-05	4,13E-05	1,03E-05	3,30E-06	8,25E-07	8,25E-07	2,06E-07
325	7,15E-03	1,43E-04	7,15E-05	3,58E-05	1,79E-03	4,47E-04	1,43E-04	7,15E-04	1,79E-04	4,47E-05	4,47E-05	1,12E-05	3,58E-06	8,94E-07	8,94E-07	2,23E-07
350	7,70E-03	1,54E-04	7,70E-05	3,85E-05	1,93E-03	4,81E-04	1,54E-04	7,70E-04	1,93E-04	4,81E-05	4,81E-05	1,20E-05	3,85E-06	9,63E-07	9,63E-07	2,41E-07
375	8,25E-03	1,65E-04	8,25E-05	4,13E-05	2,06E-03	5,16E-04	1,65E-04	8,25E-04	2,06E-04	5,16E-05	5,16E-05	1,29E-05	4,13E-06	1,03E-06	1,03E-06	2,58E-07
400	8,80E-03	1,76E-04	8,80E-05	4,40E-05	2,20E-03	5,50E-04	1,76E-04	8,80E-04	2,20E-04	5,50E-05	5,50E-05	1,38E-05	4,40E-06	1,10E-06	1,10E-06	2,75E-07
425	9,35E-03	1,87E-04	9,35E-05	4,68E-05	2,34E-03	5,84E-04	1,87E-04	9,35E-04	2,34E-04	5,84E-05	5,84E-05	1,46E-05	4,68E-06	1,17E-06	1,17E-06	2,92E-07
450	9,90E-03	1,98E-04	9,90E-05	4,95E-05	2,48E-03	6,19E-04	1,98E-04	9,90E-04	2,48E-04	6,19E-05	6,19E-05	1,55E-05	4,95E-06	1,24E-06	1,24E-06	3,09E-07
475	1,05E-02	2,09E-04	1,05E-04	5,23E-05	2,61E-03	6,53E-04	2,09E-04	1,05E-03	2,61E-04	6,53E-05	6,53E-05	1,63E-05	5,23E-06	1,31E-06	1,31E-06	3,27E-07
500	1,10E-02	2,20E-04	1,10E-04	5,50E-05	2,75E-03	6,88E-04	2,20E-04	1,10E-03	2,75E-04	6,88E-05	6,88E-05	1,72E-05	5,50E-06	1,38E-06	1,38E-06	3,44E-07
525	1,16E-02	2,31E-04	1,16E-04	5,78E-05	2,89E-03	7,22E-04	2,31E-04	1,16E-03	2,89E-04	7,22E-05	7,22E-05	1,80E-05	5,78E-06	1,44E-06	1,44E-06	3,61E-07
550	1,21E-02	2,42E-04	1,21E-04	6,05E-05	3,03E-03	7,56E-04	2,42E-04	1,21E-03	3,03E-04	7,56E-05	7,56E-05	1,89E-05	6,05E-06	1,51E-06	1,51E-06	3,78E-07
575	1,27E-02	2,53E-04	1,27E-04	6,33E-05	3,16E-03	7,91E-04	2,53E-04	1,27E-03	3,16E-04	7,91E-05	7,91E-05	1,98E-05	6,33E-06	1,58E-06	1,58E-06	3,95E-07
600	1,32E-02	2,64E-04	1,32E-04	6,60E-05	3,30E-03	8,25E-04	2,64E-04	1,32E-03	3,30E-04	8,25E-05	8,25E-05	2,06E-05	6,60E-06	1,65E-06	1,65E-06	4,13E-07
625	1,38E-02	2,75E-04	1,38E-04	6,88E-05	3,44E-03	8,59E-04	2,75E-04	1,38E-03	3,44E-04	8,59E-05	8,59E-05	2,15E-05	6,88E-06	1,72E-06	1,72E-06	4,30E-07
650	1,43E-02	2,86E-04	1,43E-04	7,15E-05	3,58E-03	8,94E-04	2,86E-04	1,43E-03	3,58E-04	8,94E-05	8,94E-05	2,23E-05	7,15E-06	1,79E-06	1,79E-06	4,47E-07
675	1,49E-02	2,97E-04	1,49E-04	7,43E-05	3,71E-03	9,28E-04	2,97E-04	1,49E-03	3,71E-04	9,28E-05	9,28E-05	2,32E-05	7,43E-06	1,86E-06	1,86E-06	4,64E-07
700	1,54E-02	3,08E-04	1,54E-04	7,70E-05	3,85E-03	9,63E-04	3,08E-04	1,54E-03	3,85E-04	9,63E-05	9,63E-05	2,41E-05	7,70E-06	1,93E-06	1,93E-06	4,81E-07
725	1,60E-02	3,19E-04	1,60E-04	7,98E-05	3,99E-03	9,97E-04	3,19E-04	1,60E-03	3,99E-04	9,97E-05	9,97E-05	2,49E-05	7,98E-06	1,99E-06	1,99E-06	4,98E-07
750	1,65E-02	3,30E-04	1,65E-04	8,25E-05	4,13E-03	1,03E-03	3,30E-04	1,65E-03	4,13E-04	1,03E-04	1,03E-04	2,58E-05	8,25E-06	2,06E-06	2,06E-06	5,16E-07
775	1,71E-02	3,41E-04	1,71E-04	8,53E-05	4,26E-03	1,07E-03	3,41E-04	1,71E-03	4,26E-04	1,07E-04	1,07E-04	2,66E-05	8,53E-06	2,13E-06	2,13E-06	5,33E-07
800	1,76E-02	3,52E-04	1,76E-04	8,80E-05	4,40E-03	1,10E-03	3,52E-04	1,76E-03	4,40E-04	1,10E-04	1,10E-04	2,75E-05	8,80E-06	2,20E-06	2,20E-06	5,50E-07
825	1,82E-02	3,63E-04	1,82E-04	9,08E-05	4,54E-03	1,13E-03	3,63E-04	1,82E-03	4,54E-04	1,13E-04	1,13E-04	2,84E-05	9,08E-06	2,27E-06	2,27E-06	5,67E-07
850	1,87E-02	3,74E-04	1,87E-04	9,35E-05	4,68E-03	1,17E-03	3,74E-04	1,87E-03	4,68E-04	1,17E-04	1,17E-04	2,92E-05	9,35E-06	2,34E-06	2,34E-06	5,84E-07
875	1,93E-02	3,85E-04	1,93E-04	9,63E-05	4,81E-03	1,20E-03	3,85E-04	1,93E-03	4,81E-04	1,20E-04	1,20E-04	3,01E-05	9,63E-06	2,41E-06	2,41E-06	6,02E-07
900	1,98E-02	3,96E-04	1,98E-04	9,90E-05	4,95E-03	1,24E-03	3,96E-04	1,98E-03	4,95E-04	1,24E-04	1,24E-04	3,09E-05	9,90E-06	2,48E-06	2,48E-06	6,19E-07
925	2,04E-02	4,07E-04	2,04E-04	1,02E-04	5,09E-03	1,27E-03	4,07E-04	2,04E-03	5,09E-04	1,27E-04	1,27E-04	3,18E-05	1,02E-05	2,54E-06	2,54E-06	6,36E-07
950	2,09E-02	4,18E-04	2,09E-04	1,05E-04	5,23E-03	1,31E-03	4,18E-04	2,09E-03	5,23E-04	1,31E-04	1,31E-04	3,27E-05	1,05E-05	2,61E-06	2,61E-06	6,53E-07
975	2,15E-02	4,29E-04	2,15E-04	1,07E-04	5,36E-03	1,34E-03	4,29E-04	2,15E-03	5,36E-04	1,34E-04	1,34E-04	3,35E-05	1,07E-05	2,68E-06	2,68E-06	6,70E-07
1000	2,20E-02	4,40E-04	2,20E-04	1,10E-04	5,50E-03	1,38E-03	4,40E-04	2,20E-03	5,50E-04	1,38E-04	1,38E-04	3,44E-05	1,10E-05	2,75E-06	2,75E-06	6,88E-07
2000	4,40E-02	8,80E-04	4,40E-04	2,20E-04	1,10E-02	2,75E-03	8,80E-04	4,40E-03	1,10E-03	2,75E-04	2,75E-04	6,88E-05	2,20E-05	5,50E-06	5,50E-06	1,38E-06
3000	6,60E-02	1,32E-03	6,60E-04	3,30E-04	1,65E-02	4,13E-03	1,32E-03	6,60E-03	1,65E-03	4,13E-04	4,13E-04	1,03E-04	3,30E-05	8,25E-06	8,25E-06	2,06E-06
4000	8,80E-02	1,76E-03	8,80E-04	4,40E-04	2,20E-02	5,50E-03	1,76E-03	8,80E-03	2,20E-03	5,50E-04	5,50E-04	1,38E-04	4,40E-05	1,10E-05	1,10E-05	2,75E-06
5000	1,10E-01	2,20E-03	1,10E-03	5,50E-04	2,75E-02	6,88E-03	2,20E-03	1,10E-02	2,75E-03	6,88E-04	6,88E-04	1,72E-04	5,50E-05	1,38E-05	1,38E-05	3,44E-06
6000	1,32E-01	2,64E-03	1,32E-03	6,60E-04	3,30E-02	8,25E-03	2,64E-03	1,32E-02	3,30E-03	8,25E-04	8,25E-04	2,06E-04	6,60E-05	1,65E-05	1,65E-05	4,13E-06
7000	1,54E-01	3,08E-03	1,54E-03	7,70E-04	3,85E-02	9,63E-03	3,08E-03	1,54E-02	3,85E-03	9,63E-04	9,63E-04	2,41E-04	7,70E-05	1,93E-05	1,93E-05	4,81E-06
8000	1,76E-01	3,52E-03	1,76E-03	8,80E-04	4,40E-02	1,10E-02	3,52E-03	1,76E-02	4,40E-03	1,10E-03	1,10E-03	2,75E-04	8,80E-05	2,20E-05	2,20E-05	5,50E-06
9000	1,98E-01	3,96E-03	1,98E-03	9,90E-04	4,95E-02	1,24E-02	3,96E-03	1,98E-02	4,95E-03	1,24E-03	1,24E-03	3,09E-04	9,90E-05	2,48E-05	2,48E-05	6,19E-06
10000	2,20E-01	4,40E-03	2,20E-03	1,10E-03	5,50E-02	1,38E-02	4,40E-03	2,20E-02	5,50E-03	1,38E-03	1,38E-03	3,44E-04	1,10E-04	2,75E-05	2,75E-05	6,88E-06

TABLE 5.6

Pt/Pfi

Afi [m2]		Sprinkler	Sprinkler 1Wat. Suply	Sprinkler 2 Wat. Suply	Detect. by heat	Detect. By smoke	Work Firemen	Off Site Firemen	Off Site Firemen Detect. by heat	Off Site Firemen Detect. By smoke	Off Site Firemen Detect. by heat Autom. Transm.	Off Site Firemen Detect. By smoke Autom. Transm.	Sprinkler Off Site Firemen Detect. by heat	Sprinkler Off Site Firemen Detect. By smoke	Sprinkler Off Site Firemen Detect. by heat Autom. Transm.	Sprinkler Off Site Firemen Detect. By smoke Autom. Transm.
Probability of failure of the Active measures		0,02	0,02 0,5	0,02 0,25	0,25	0,0625	0,02	0,1	0,1 0,25	0,1 0,0625	0,1 0,25 0,25	0,1 0,0625 0,25	0,02 0,1 0,25	0,02 0,1 0,0625	0,02 0,1 0,25 0,25	0,02 0,1 0,0625 0,25
→		0,02	0,01	0,005	0,25	0,0625	0,02	0,1	0,025	0,00625	0,00625	0,0015625	0,0005	0,000125	0,000125	0,00003125
1	3,286364	164,31818	328,636364	657,272727	13,14545455	52,58181818	164,3181818	32,86363636	131,4545455	525,8181818	525,8181818	2103,272727	6572,727273	26290,90909	26290,90909	105163,6364
25	0,131455	6,5727273	13,1454545	26,2909091	0,525818182	2,103272727	6,572727273	1,314545455	5,258181818	21,03272727	21,03272727	84,13090909	262,9090909	1051,636364	1051,636364	4206,545455
50	0,065727	3,2863636	6,57272727	13,1454545	0,262909091	1,051636364	3,286363636	0,657272727	2,629090909	10,51636364	10,51636364	42,06545455	131,4545455	525,8181818	525,8181818	2103,272727
75	0,043818	2,1909091	4,38181818	8,76363636	0,175272727	0,701090909	2,190909091	0,438181818	1,752727273	7,010909091	7,010909091	28,04363636	87,63636364	350,5454545	350,5454545	1402,181818
100	0,032864	1,6431818	3,28636364	6,57272727	0,131454545	0,525818182	1,643181818	0,328636364	1,314545455	5,258181818	5,258181818	21,03272727	65,72727273	262,9090909	262,9090909	1051,636364
125	0,026291	1,3145455	2,62909091	5,25818182	0,105163636	0,420654545	1,314545455	0,262909091	1,051636364	4,206545455	4,206545455	16,82618182	52,58181818	210,3272727	210,3272727	841,3090909
150	0,021909	1,0954545	2,19090909	4,38181818	0,087636364	0,350545455	1,095454545	0,219090909	0,876363636	3,505454545	3,505454545	14,02181818	43,81818182	175,2727273	175,2727273	701,0909091
175	0,018779	0,938961	1,87792208	3,75584416	0,075116883	0,300467532	0,938961039	0,187792208	0,751168831	3,004675325	3,004675325	12,0187013	37,55844156	150,2337662	150,2337662	600,9350649
200	0,016432	0,8215909	1,64318182	3,28636364	0,065727273	0,262909091	0,821590909	0,164318182	0,657272727	2,629090909	2,629090909	10,51636364	32,86363636	131,4545455	131,4545455	525,8181818
225	0,014606	0,730303	1,46060606	2,92121212	0,058424242	0,23369697	0,73030303	0,146060606	0,584242424	2,336969697	2,336969697	9,347878788	29,21212121	116,8484848	116,8484848	467,3939394
250	0,013145	0,6572727	1,31454545	2,62909091	0,052581818	0,210327273	0,657272727	0,131454545	0,525818182	2,103272727	2,103272727	8,413090909	26,29090909	105,1636364	105,1636364	420,6545455
275	0,01195	0,5975207	1,19504132	2,39008264	0,047801653	0,191206612	0,597520661	0,119504132	0,478016529	1,912066116	1,912066116	7,648264463	23,90082645	95,60330579	95,60330579	382,4132231
300	0,010955	0,5477273	1,09545455	2,19090909	0,043818182	0,175272727	0,547727273	0,109545455	0,438181818	1,752727273	1,752727273	7,010909091	21,90909091	87,63636364	87,63636364	350,5454545
325	0,010112	0,5055944	1,01118881	2,02237762	0,040447552	0,16179021	0,505594406	0,101118881	0,404475524	1,617902098	1,617902098	6,471608392	20,22377622	80,8951049	80,8951049	323,5804196
350	0,00939	0,4694805	0,93896104	1,87792208	0,037558442	0,150233766	0,469480519	0,093896104	0,375584416	1,502337662	1,502337662	6,009350649	18,77922078	75,11688312	75,11688312	300,4675325
375	0,008764	0,4381818	0,87636364	1,75272727	0,035054545	0,140218182	0,438181818	0,087636364	0,350545455	1,402181818	1,402181818	5,608727273	17,52727273	70,10909091	70,10909091	280,4363636
400	0,008216	0,4107955	0,82159091	1,64318182	0,032863636	0,131454545	0,410795455	0,082159091	0,328636364	1,314545455	1,314545455	5,258181818	16,43181818	65,72727273	65,72727273	262,9090909
425	0,007733	0,386631	0,77326203	1,54652406	0,030930481	0,123721925	0,386631016	0,077326203	0,309304813	1,237219251	1,237219251	4,948877005	15,46524064	61,86096257	61,86096257	247,4438503
450	0,007303	0,3651515	0,73030303	1,46060606	0,029212121	0,116848485	0,365151515	0,073030303	0,292121212	1,168484848	1,168484848	4,673939394	14,60606061	58,42424242	58,42424242	233,6969697
475	0,006919	0,345933	0,69186603	1,38373206	0,027674641	0,110698565	0,345933014	0,069186603	0,276746411	1,106985646	1,106985646	4,427942584	13,83732057	55,3492823	55,3492823	221,3971292
500	0,006573	0,3286364	0,65727273	1,31454545	0,026290909	0,105163636	0,328636364	0,065727273	0,262909091	1,051636364	1,051636364	4,206545455	13,14545455	52,58181818	52,58181818	210,3272727
525	0,00626	0,312987	0,62597403	1,25194805	0,025038961	0,100155844	0,312987013	0,062597403	0,25038961	1,001558442	1,001558442	4,006233766	12,51948052	50,07792208	50,07792208	200,3116883
550	0,005975	0,2987603	0,59752066	1,19504132	0,023900826	0,095603306	0,298760331	0,059752066	0,239008264	0,956033058	0,956033058	3,824132231	11,95041322	47,80165289	47,80165289	191,2066116
575	0,005715	0,2857708	0,5715415	1,143083	0,02286166	0,09144664	0,285770751	0,05715415	0,228616601	0,914466403	0,914466403	3,657865613	11,43083004	45,72332016	45,72332016	182,8932806
600	0,005477	0,2738636	0,54772727	1,09545455	0,021909091	0,087636364	0,273863636	0,054772727	0,219090909	0,876363636	0,876363636	3,505454545	10,95454545	43,81818182	43,81818182	175,2727273
625	0,005258	0,2629091	0,52581818	1,05163636	0,021032727	0,084130909	0,262909091	0,052581818	0,210327273	0,841309091	0,841309091	3,365236364	10,51636364	42,06545455	42,06545455	168,2618182
650	0,005056	0,2527972	0,50559441	1,01118881	0,020223776	0,080895105	0,252797203	0,050559441	0,202237762	0,808951049	0,808951049	3,235804196	10,11188811	40,44755245	40,44755245	161,7902098
675	0,004869	0,2434343	0,48686869	0,97373737	0,019474747	0,07789899	0,243434343	0,048686869	0,194747475	0,778989899	0,778989899	3,115959596	9,737373737	38,94949495	38,94949495	155,7979798
700	0,004695	0,2347403	0,46948052	0,93896104	0,018779221	0,075116883	0,23474026	0,046948052	0,187792208	0,751168831	0,751168831	3,004675325	9,38961039	37,55844156	37,55844156	150,2337662
725	0,004533	0,2266458	0,45329154	0,90658307	0,018131661	0,072526646	0,226645768	0,045329154	0,181316614	0,725266458	0,725266458	2,901065831	9,065830721	36,26332288	36,26332288	145,0532915
750	0,004382	0,2190909	0,43818182	0,87636364	0,017527273	0,070109091	0,219090909	0,043818182	0,175272727	0,701090909	0,701090909	2,804363636	8,763636364	35,05454545	35,05454545	140,2181818
775	0,00424	0,2120235	0,42404692	0,84809384	0,016961877	0,067847507	0,21202346	0,042404692	0,169618768	0,678475073	0,678475073	2,713900293	8,480938416	33,92375367	33,92375367	135,6950147
800	0,004108	0,2053977	0,41079545	0,82159091	0,016431818	0,065727273	0,205397727	0,041079545	0,164318182	0,657272727	0,657272727	2,629090909	8,215909091	32,86363636	32,86363636	131,4545455
825	0,003983	0,1991736	0,39834711	0,79669421	0,015933884	0,063735537	0,199173554	0,039834711	0,159338843	0,637355372	0,637355372	2,549421488	7,966942149	31,8677686	31,8677686	127,4710744
850	0,003866	0,1933155	0,38663102	0,77326203	0,015465241	0,061860963	0,193315508	0,038663102	0,154652406	0,618609626	0,618609626	2,474438503	7,732620321	30,93048128	30,93048128	123,7219251
875	0,003756	0,1877922	0,37558442	0,75116883	0,015023377	0,060093506	0,187792208	0,037558442	0,150233766	0,600935065	0,600935065	2,40374026	7,511688312	30,04675325	30,04675325	120,187013
900	0,003652	0,1825758	0,36515152	0,73030303	0,014606061	0,058424242	0,182575758	0,036515152	0,146060606	0,58424242	0,584242424	2,336969697	7,303030303	29,21212121	29,21212121	116,8484848
925	0,003553	0,1776413	0,35528256	0,71056511	0,014211302	0,056845209	0,177641278	0,035528256	0,142113022	0,568452088	0,568452088	2,273808354	7,105651106	28,42260442	28,42260442	113,6904177
950	0,003459	0,1729665	0,34593301	0,69186603	0,013837321	0,055349282	0,172966507	0,034593301	0,138373206	0,553492823	0,553492823	2,213971292	6,918660287	27,67464115	27,67464115	110,6985646
975	0,003371	0,1685315	0,33706294	0,67412587	0,013482517	0,05393007	0,168531469	0,033706294	0,134825175	0,539300699	0,539300699	2,157202797	6,741258741	26,96503497	26,96503497	107,8601399
1000	0,003286	0,1643182	0,32863636	0,65727273	0,013145455	0,052581818	0,164318182	0,032863636	0,131454545	0,525818182	0,525818182	2,103272727	6,572727273	26,29090909	26,29090909	105,1636364
2000	0,001643	0,0821591	0,16431818	0,32863636	0,006572727	0,026290909	0,082159091	0,016431818	0,065727273	0,262909091	0,262909091	1,051636364	3,286363636	13,14545455	13,14545455	52,58181818
3000	0,001095	0,0547727	0,10954545	0,21909091	0,004381818	0,017527273	0,054772727	0,010954545	0,043818182	0,175272727	0,175272727	0,701090909	2,190909091	8,763636364	8,763636364	35,05454545
4000	0,000822	0,0410795	0,08215909	0,16431818	0,003286364	0,013145455	0,041079545	0,008215909	0,032863636	0,131454545	0,131454545	0,525818182	1,643181818	6,572727273	6,572727273	26,29090909
5000	0,000657	0,0328636	0,06572727	0,13145455	0,002629091	0,010516364	0,032863636	0,006572727	0,026290909	0,105163636	0,105163636	0,420654545	1,314545455	5,258181818	5,258181818	21,03272727
6000	0,000548	0,0273864	0,05477273	0,10954545	0,002190909	0,008763636	0,027386364	0,005477273	0,021909091	0,087636364	0,087636364	0,350545455	1,095454545	4,381818182	4,381818182	17,52727273
7000	0,000469	0,023474	0,04694805	0,0938961	0,001877922	0,007511688	0,023474026	0,004694805	0,018779221	0,075116883	0,075116883	0,300467532	0,938961039	3,755844156	3,755844156	15,02337662
8000	0,000411	0,0205398	0,04107955	0,08215909	0,001643182	0,006572727	0,020539773	0,004107955	0,016431818	0,065727273	0,065727273	0,262909091	0,821590909	3,286363636	3,286363636	13,14545455
9000	0,000365	0,0182576	0,03651515	0,0730303	0,001460606	0,005842424	0,018257576	0,003651515	0,014606061	0,058424242	0,058424242	0,23369697	0,73030303	2,921212121	2,921212121	11,68484848
10000	0,000329	0,0164318	0,03286364	0,06572727	0,001314545	0,005258182	0,016431818	0,003286364	0,013145455	0,052581818	0,052581818	0,210327273	0,657272727	2,629090909	2,629090909	10,51636364

TABLE 5.7

BETAfi,t

Afi [m2]		Sprinkler	Sprinkler 1Wat. Suply	Sprinkler 2 Wat. Suply	Detect. by heat	Detect. By smoke	Work Firemen	Off Site Firemen	Off Site Firemen Detect. by heat	Off Site Firemen Detect. By smoke	Off Site Firemen Detect. by heat Autom. Transm.	Off Site Firemen Detect. By smoke Autom. Transm.	Sprinkler Off Site Firemen Detect. by heat	Sprinkler Off Site Firemen Detect. By smoke	Sprinkler Off Site Firemen Detect. by heat Autom. Transm.	Sprinkler Off Site Firemen Detect. By smoke Autom. Transm.
Probability of failure of the Active measures		0,02	0,02 0,5	0,02 0,25	0,25	0,0625	0,02	0,1	0,1 0,25	0,1 0,0625	0,1 0,25 0,25	0,1 0,0625 0,25	0,02 0,1 0,25	0,02 0,1 0,0625	0,02 0,1 0,25 0,25	0,02 0,1 0,0625 0,25
→		0,02	0,01	0,005	0,25	0,0625	0,02	0,1	0,025	0,00625	0,00625	0,0015625	0,0005	0,000125	0,000125	0,00003125
1	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE
25	1,1195425	- INFINITE	- INFINITE	- INFINITE	-0,064761707	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE
50	1,50839242	- INFINITE	- INFINITE	- INFINITE	0,634402113	- INFINITE	- INFINITE	-0,405032097	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE
75	1,70799922	- INFINITE	- INFINITE	- INFINITE	0,933532647	-0,527541033	- INFINITE	0,155580437	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE
100	1,84028067	- INFINITE	- INFINITE	- INFINITE	1,119542503	-0,064761707	- INFINITE	0,443681074	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE
125	1,93834239	- INFINITE	- INFINITE	- INFINITE	1,252665243	0,200219574	- INFINITE	0,634402113	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE
150	2,01582225	- INFINITE	- INFINITE	- INFINITE	1,355456334	0,383847691	- INFINITE	0,775266926	-1,157000042	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE
175	2,07964149	-1,5461092	- INFINITE	- INFINITE	1,438706931	0,523056087	-1,546109161	0,886061571	-0,678171546	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE
200	2,13374733	-0,9214455	- INFINITE	- INFINITE	1,508392415	0,634402113	-0,921445462	0,976863248	-0,405032097	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE
225	2,1806045	-0,6137293	- INFINITE	- INFINITE	1,56814167	0,72672492	-0,613729298	1,053479082	-0,212758096	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE
250	2,22187737	-0,4050321	- INFINITE	- INFINITE	1,620319381	0,805285936	-0,405032097	1,119542503	-0,064761707	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE
275	2,2587119	-0,2469346	- INFINITE	- INFINITE	1,666553544	0,873458248	-0,246934633	1,177468221	0,055132432	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE
300	2,29194484	-0,1199214	- INFINITE	- INFINITE	1,707999218	0,933532647	-0,119921424	1,228950168	0,155580437	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE
325	2,32215825	-0,0140233	- INFINITE	- INFINITE	1,745515874	0,987126896	-0,014023271	1,275202521	0,241780072	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE
350	2,34987965	0,0765749	-1,5461092	- INFINITE	1,779749255	1,035432433	0,076574906	1,317139322	0,317098738	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE
375	2,37545464	0,1555804	-1,157	- INFINITE	1,811204129	1,079340564	0,155580437	1,355456334	0,383847691	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE
400	2,39917426	0,2255001	-0,9214455	- INFINITE	1,840280675	1,119542503	0,225500116	1,390694706	0,443681074	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE
425	2,42129317	0,2881109	-0,7496328	- INFINITE	1,867292667	1,156581675	0,288110868	1,423290996	0,49782102	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE
450	2,44199327	0,3447224	-0,6137293	- INFINITE	1,89250386	1,190890089	0,344722366	1,453586265	0,547197487	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE
475	2,46145646	0,3963237	-0,5011464	- INFINITE	1,916123438	1,222822448	0,396323685	1,481876097	0,592533524	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE
500	2,47979187	0,4436811	-0,4050321	- INFINITE	1,938342393	1,252665243	0,443681074	1,508392415	0,634402113	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE
525	2,49714503	0,4874005	-0,3212085	- INFINITE	1,959297151	1,280664037	0,487400484	1,53333076	0,673264822	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE
550	2,5135887	0,5279685	-0,2469346	- INFINITE	1,979124136	1,307016646	0,527968496	1,556859388	0,709496817	-1,706398507	-1,706398507	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE
575	2,52923201	0,565783	-0,1803005	- INFINITE	1,997941581	1,331900421	0,565783012	1,579119271	0,743409601	-1,368784979	-1,368784979	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE
600	2,54414772	0,6011692	-0,1199214	- INFINITE	2,015822247	1,355456334	0,601169177	1,600237738	0,775266926	-1,157000042	-1,157000042	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE
625	2,55837222	0,6344021	-0,0647617	- INFINITE	2,032866178	1,377811714	0,634402113	1,620319381	0,805285936	-0,999853	-0,999853	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE
650	2,57197826	0,6657137	-0,0140233	- INFINITE	2,049146133	1,3990757	0,665713742	1,639455149	0,833654212	-0,874038051	-0,874038051	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE
675	2,58500222	0,6952973	0,03292143	-1,9388062	2,064716682	1,419348337	0,695297331	1,657722351	0,860534328	-0,768786776	-0,768786776	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE
700	2,59751687	0,7233234	0,07657491	-1,5461092	2,07964149	1,438706931	0,72332341	1,675193744	0,886061571	-0,678171546	-0,678171546	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE
725	2,60955858	0,7499386	0,11734983	-1,3200042	2,093966032	1,457228791	0,749938636	1,691932994	0,910358722	-0,598558927	-0,598558927	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE
750	2,62116373	0,7752669	0,15558044	-1,157	2,107726687	1,47497758	0,775266926	1,707999218	0,933532647	-0,527541033	-0,527541033	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE
775	2,63229595	0,7994197	0,19155095	-1,0282929	2,120978024	1,492016963	0,799419695	1,72343789	0,955672022	-0,46343871	-0,46343871	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE
800	2,64306436	0,8224947	0,22550012	-0,9214455	2,13374733	1,508392415	0,822494712	1,738289939	0,976863248	-0,405032097	-0,405032097	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE
825	2,65346898	0,8445772	0,25762802	-0,8298707	2,146061888	1,524149411	0,844577244	1,752605385	0,997179086	-0,351399194	-0,351399194	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE
850	2,6635098	0,8657435	0,28811087	-0,7496328	2,157958079	1,539337973	0,865743459	1,766411515	1,016680926	-0,301831733	-0,301831733	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE
875	2,67325959	0,8860616	0,31709874	-0,6781715	2,169472282	1,553989932	0,886061571	1,779749255	1,035432433	-0,2557681	-0,2557681	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE
900	2,68271833	0,905593	0,34472237	-0,6137293	2,180604497	1,56814167	0,90559297	1,792641342	1,053479082	-0,212758096	-0,212758096	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE
925	2,69184966	0,9243922	0,37109771	-0,5550362	2,191409294	1,58182047	0,924392225	1,805115062	1,070875442	-0,172434511	-0,172434511	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE
950	2,70076271	0,9425071	0,39632368	-0,5011464	2,201868483	1,595062713	0,942507086	1,817197699	1,087657893	-0,134491529	-0,134491529	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE
975	2,70934834	0,9599853	0,42049237	-0,4513345	2,212018444	1,607886588	0,9599853	1,828911991	1,103867362	-0,098672217	-0,098672217	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE
1000	2,71775207	0,9768632	0,44368107	-0,4050321	2,221877367	1,620319381	0,976863248	1,840280675	1,119542503	-0,064761707	-0,064761707	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE
2000	2,9396324	1,3906947	0,97686325	0,44368107	2,479791874	1,938342393	1,390694706	2,13374733	1,508392415	0,634402113	0,634402113	- INFINITE	- INFINITE	- INFINITE	- INFINITE	- INFINITE
3000	3,06303264	1,6002377	1,22895017	0,77526693	2,621163731	2,107726687	1,600237738	2,291944838	1,707999218	0,933532647	0,933532647	-0,527541033	- INFINITE	- INFINITE	- INFINITE	- INFINITE
4000	3,14816134	1,7382899	1,39069471	0,97686325	2,717752068	2,221877367	1,738289939	2,399174264	1,840280675	1,119542503	1,119542503	-0,064761707	- INFINITE	- INFINITE	- INFINITE	- INFINITE
5000	3,21277184	1,8402807	1,50839242	1,1195425	2,790766302	2,307388058	1,840280675	2,479791874	1,938342393	1,252665243	1,252665243	0,200219574	- INFINITE	- INFINITE	- INFINITE	- INFINITE
6000	3,2648677	1,9206709	1,60023774	1,22895017	2,849265002	2,375454642	1,920670911	2,544147719	2,015822247	1,355456334	1,355456334	0,383847691	- INFINITE	- INFINITE	- INFINITE	- INFINITE
7000	3,30823241	1,9867639	1,67519374	1,31713932	2,898013918	2,431806934	1,986763891	2,597516868	2,07964149	1,438706931	1,438706931	0,523056087	-1,546109161	- INFINITE	- INFINITE	- INFINITE
8000	3,34548531	2,0427251	1,73828994	1,39069471	2,939632395	2,479791874	2,0427251	2,643064363	2,13374733	1,508392415	1,508392415	0,634402113	-0,921445462	- INFINITE	- INFINITE	- INFINITE
9000	3,37779056	2,0911466	1,79264134	1,45358626	2,975866664	2,521519491	2,091146598	2,682718332	2,180604497	1,56814167	1,56814167	0,72672492	-0,613729298	- INFINITE	- INFINITE	- INFINITE
10000	3,40689439	2,1337473	1,84028067	1,50839242	3,008026397	2,558372216	2,13374733	2,717752068	2,221877367	1,620319381	1,620319381	0,805285936	-0,405032097	- INFINITE	- INFINITE	- INFINITE

TABLE 5.8

GAMMAqf

Afi [m2]		Sprinkler	Sprinkler 1Wat. Suply	Sprinkler 2 Wat. Suply	Detect. by heat	Detect. By smoke	Work Firemen	Off Site Firemen	Off Site Firemen Detect. by heat	Off Site Firemen Detect. By smoke	Off Site Firemen Detect. by heat Autom. Transm.	Off Site Firemen Detect. By smoke Autom. Transm.	Sprinkler Off Site Firemen Detect. by heat	Sprinkler Off Site Firemen Detect. By smoke	Sprinkler Off Site Firemen Detect. by heat Autom. Transm.	Sprinkler Off Site Firemen Detect. By smoke Autom. Transm.
Probability of failure of the Active measures		0,02	0,02 0,5	0,02 0,25	0,25	0,0625	0,02	0,1	0,1 0,25	0,1 0,0625	0,1 0,25 0,25	0,1 0,0625 0,25	0,02 0,1 0,25	0,02 0,1 0,0625	0,02 0,1 0,25 0,25	0,02 0,1 0,0625 0,25
→		0,02	0,01	0,005	0,25	0,0625	0,02	0,1	0,025	0,00625	0,00625	0,0015625	0,0005	0,000125	0,000125	0,00003125
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	**1,104256**	0	0	0	0,807637214	0	0	0	0	0	0	0	0	0	0	0
50	1,230404	0	0	0	0,968473421	0	0	0,741444431	0	0	0	0	0	0	0	0
75	1,301852	0	0	0	1,049543424	0,719247536	0	0,854432687	0	0	0	0	0	0	0	0
100	**1,35187**	0	0	0	1,104256075	0,807637214	0	0,920877278	0	0	0	0	0	0	0	0
125	1,39037	0	0	0	1,145588242	0,864323109	0	0,968473421	0	0	0	0	0	0	0	0
150	1,421663	0	0	0	1,1788033	0,906556274	0	1,00563203	0,616866391	0	0	0	0	0	0	0
175	1,448028	0,5618825	0	0	1,206562495	0,940319126	0,561882488	1,036124576	0,693040049	0	0	0	0	0	0	0
200	1,470802	0,6530586	0	0	1,230404158	0,968473421	0,653058622	1,06198182	0,741444431	0	0	0	0	0	0	0
225	1,490842	0,70411	0	0	1,251294706	0,992627736	0,704110027	1,084427552	0,777989069	0	0	0	0	0	0	0
250	**1,508738**	0,7414444	0	0	1,269882201	1,013781294	0,741444431	1,104256075	0,807637214	0	0	0	0	0	0	0
275	1,524905	0,7713346	0	0	1,286624345	1,032598045	0,771334582	1,122011784	0,83269089	0	0	0	0	0	0	0
300	1,53965	0,7964261	0	0	1,301852296	1,049543424	0,796426135	1,138087881	0,854432687	0	0	0	0	0	0	0
325	1,553187	0,8181234	0	0	1,315817693	1,06495496	0,818123434	1,152772172	0,87366109	0	0	0	0	0	0	0
350	1,565717	0,8372734	0,56188249	0	1,328712392	1,079087851	0,837273384	1,166286631	0,890909903	0	0	0	0	0	0	0
375	1,577372	0,8544327	0,61686639	0	1,34068898	1,092136788	0,854432687	1,1788033	0,906556274	0	0	0	0	0	0	0
400	1,588263	0,8699882	0,65305862	0	1,351870239	1,104256075	0,8699882	1,190458177	0,920877278	0	0	0	0	0	0	0
425	1,598489	0,884221	0,68100479	0	1,362353097	1,115569249	0,884221027	1,201363244	0,934082442	0	0	0	0	0	0	0
450	1,608121	0,8973434	0,70411003	0	1,372220599	1,126175971	0,897343427	1,211606419	0,946334782	0	0	0	0	0	0	0
475	1,617233	0,9095191	0,72396127	0	1,381538702	1,13615965	0,909519063	1,221266228	0,957763631	0	0	0	0	0	0	0
500	1,625865	0,9208773	0,74144443	0	1,390369524	1,145588242	0,920877278	1,230404158	0,968473421	0	0	0	0	0	0	0
525	1,634078	0,9315223	0,75711224	0	1,39875615	1,154521341	0,931522308	1,239072753	0,978549769	0	0	0	0	0	0	0
550	1,6419	0,9415393	0,77133458	0	1,4067437	1,163006939	0,941539301	1,247317954	0,988063273	0,540789954	0,540789954	0	0	0	0	0
575	1,649377	0,9509991	0,78437448	0	1,414371759	1,171089317	0,950999118	1,255178478	0,997073541	0,5862439	0,5862439	0	0	0	0	0
600	1,656539	0,9599603	0,79642614	0	1,421662838	1,1788033	0,959960317	1,262690127	1,00563203	0,616866391	0,616866391	0	0	0	0	0
625	1,663398	0,9684734	0,80763721	0	1,428651657	1,186181121	0,968473421	1,269882201	1,013781294	0,640748821	0,640748821	0	0	0	0	0
650	1,669985	0,9765816	0,81812343	0	1,435362807	1,193250599	0,976581616	1,276780391	1,021558764	0,660633904	0,660633904	0	0	0	0	0
675	1,676316	0,9843211	0,82797716	0,51165588	1,441814157	1,200037852	0,984321068	1,283406532	1,028997401	0,67782096	0,67782096	0	0	0	0	0
700	1,682421	0,9917244	0,83727338	0,56188249	1,448028001	1,206562495	0,991724431	1,289781701	1,036124576	0,693040049	0,693040049	0	0	0	0	0
725	1,688318	0,9988201	0,84607485	0,59314522	1,454019664	1,212845045	0,998820087	1,295924441	1,042965785	0,706746579	0,706746579	0	0	0	0	0
750	1,694019	1,005632	0,85443269	0,61686639	1,459801113	1,218902197	1,00563203	1,301852296	1,049543424	0,719247536	0,719247536	0	0	0	0	0
775	1,699507	1,0121823	0,86239125	0,63634981	1,465392392	1,224751327	1,012182283	1,307578341	1,05587587	0,730760171	0,730760171	0	0	0	0	0
800	1,704832	1,0184904	0,8699882	0,65305862	1,470802442	1,230404158	1,018490364	1,313114419	1,06198182	0,741444431	0,741444431	0	0	0	0	0
825	1,709994	1,0245734	0,87725527	0,66778348	1,476040474	1,235872879	1,024573379	1,318476192	1,067876898	0,751423065	0,751423065	0	0	0	0	0
850	1,714989	1,0304468	0,88422103	0,68100479	1,481119846	1,24117171	1,030446786	1,323671193	1,073574137	0,760791385	0,760791385	0	0	0	0	0
875	1,719854	1,0361246	0,8909099	0,69304005	1,486054212	1,246308925	1,036124576	1,328712392	1,079087851	0,769626026	0,769626026	0	0	0	0	0
900	1,724586	1,0416195	0,89734343	0,70411003	1,490841834	1,251294706	1,041619476	1,33360618	1,084427552	0,777989069	0,777989069	0	0	0	0	0
925	1,729167	1,0469429	0,90354099	0,71437647	1,495504617	1,256136321	1,046942853	1,338360892	1,089605903	0,785931692	0,785931692	0	0	0	0	0
950	1,73365	1,0521046	0,90951906	0,72396127	1,500033267	1,26084452	1,052104622	1,342985091	1,09463058	0,793497084	0,793497084	0	0	0	0	0
975	1,737979	1,0571151	0,91529346	0,73295898	1,504442172	1,265423829	1,057115125	1,347485805	1,09951096	0,800721967	0,800721967	0	0	0	0	0
1000	**1,742226**	1,0619818	0,92087728	0,74144443	1,508738019	1,269882201	1,06198182	1,351870239	1,104256075	0,807637214	0,807637214	0	0	0	0	0
2000	1,858094	1,1904582	1,06198182	0,92087728	1,625865082	1,390369524	1,190458177	1,470802442	1,230404158	0,968473421	0,968473421	0	0	0	0	0
3000	1,925665	1,2626901	1,13808788	1,00563203	1,694019479	1,459801113	1,262690127	1,539649835	1,301852296	1,049543424	1,049543424	0,719247536	0	0	0	0
4000	1,973598	1,3131144	1,19045818	1,06198182	1,742226387	1,508738019	1,313114419	1,588262952	1,351870239	1,104256075	1,104256075	0,807637214	0	0	0	0
5000	**2,010701**	1,3518702	1,23040416	1,10425608	1,77956205	1,546553287	1,351870239	1,625865082	1,390369524	1,145588242	1,145588242	0,864323109	0	0	0	0
6000	2,041073	1,3833409	1,26269013	1,13808788	1,810034952	1,577372362	1,383340914	1,656538719	1,421662838	1,1788033	1,1788033	0,906556274	0	0	0	0
7000	**2,066665**	1,4098351	1,2897817	1,16628663	1,835811413	1,603374028	1,409835086	1,68242145	1,448028001	1,206562495	1,206562495	0,940319126	0,561882488	0	0	0
8000	2,088878	1,4327117	1,31311442	1,19045818	1,858093771	1,625865082	1,432711679	1,704832436	1,470802442	1,230404158	1,230404158	0,968473421	0,653058622	0	0	0
9000	2,108309	1,4528382	1,33360618	1,21160642	1,87770128	1,645686757	1,452838202	1,724585951	1,490841834	1,251294706	1,251294706	0,992627736	0,704110027	0	0	0
10000	**2,125951**	1,4708024	1,35187024	1,23040416	1,895266422	1,663397636	1,470802442	1,742226387	1,508738019	1,269882201	1,269882201	1,013781294	0,741444431	0	0	0

TABLE 5.9

5.4.5 DETERMINATION OF THE DIFFERENTIATION FACTORS γ_{q1}, γ_{q2} AND γ_n

REFERENCE CASE AND INFLUENCE OF THE COMPARTMENT AREA

The reference case is represented by

- a fire compartment of 25m² (A_{fi}) in an office building
- a building life of 55 years
- a probability of severe fire per m² equal to 4 . 10^{-7} (see Table 5.2)

For this reference case, the probability to have a fully engulfed compartment is (see 5.3.2):

$$p_{fi} = p_1 \cdot A_{fi} \text{ ...(number of years)}$$
$$p_{fi} = 4 \,.\, 10^{-7} \,.\, 25 \,.\, 55 = 5{,}5 \,.\, 10^{-4}$$

According to chapter 5.4.3, the probability of the structural failure in case of fire has to fullfill then:

$$p_{f,fi} \leq \frac{p_t}{p_{fi}} = \frac{7{,}23 \,.\, 10^{-5}}{5{,}5 \,.\, 10^{-4}} = 0{,}131$$

and the corresponding safety index $\beta_{fi,t}$ is equal to 1,12.

This factor β_{fi} of 1,12 implies a safety factor γ_{q1} of 1,1.

In the same way, we can obtain other safety coefficients γ_{q1} for other areas A_{fi}.

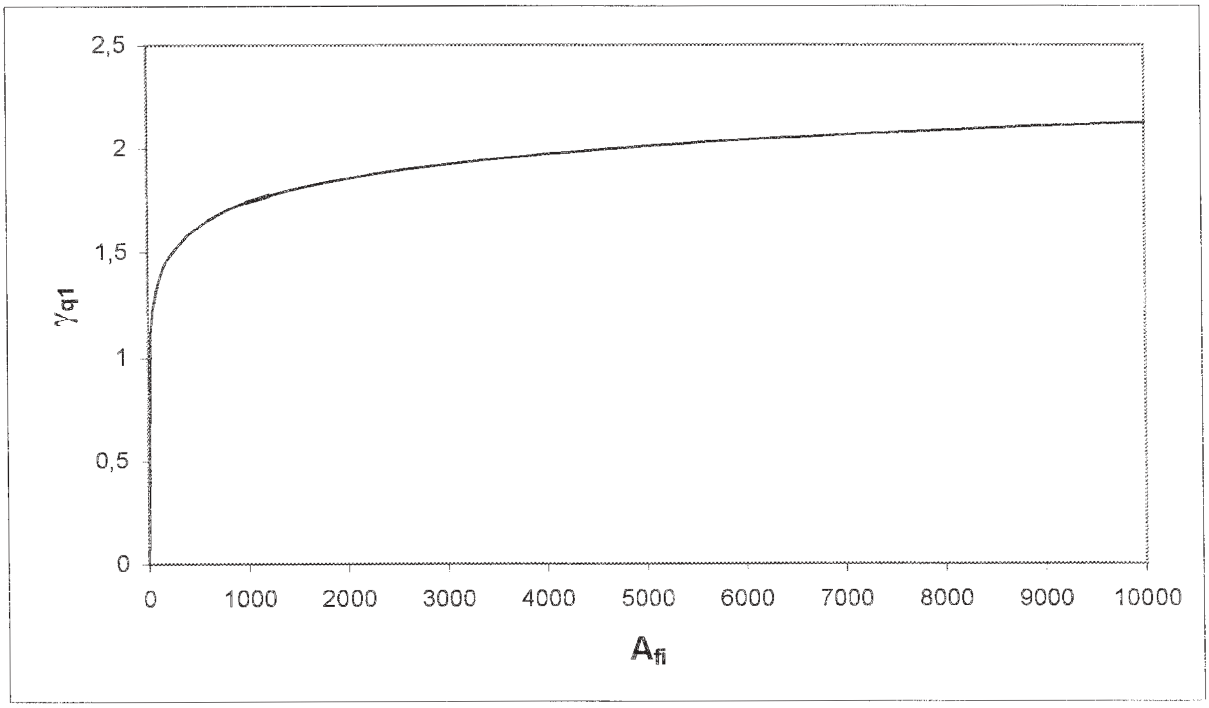


FIGURE 5.5: Safety factor γ_{q1} as a function of A_{fi}

A_{fi} [m²]	p_{fi}	p_t / p_{fi}	β_{fi}	γ_{q1}
25	$5{,}5 \cdot 10^{-4}$	0,13145	1,12	1,1
100	$2{,}2 \cdot 10^{-3}$	0,03286	1,84	1,35
250	$5{,}5 \cdot 10^{-3}$	0,01315	2,22	1,5
1000	$2{,}2 \cdot 10^{-2}$	0,00328	2,72	1,74
2500	$5{,}5 \cdot 10^{-2}$	0,00131	3,01	1,9
5000	$11 \cdot 10^{-2}$	0,00066	3,21	2,0
7000	$15{,}4 \cdot 10^{-2}$	0,00047	3,31	2,1
10000	$22 \cdot 10^{-2}$	0,00033	3,41	2,13

TABLE 5.10: Differentiation factor γ_{q1} - Influence of the compartment area

RISK OF FIRE ACTIVATION ACCORDING TO OCCUPANCY

The previous calculation has been based on a probability of fire p_1 of 4.10^{-7} per year and m² corresponding to offices. It is obvious that the risk is much higher for a fireworks industry and lower for a museum with Grecian statues. We can calculate the γ_{qf} factor for the following building categories characterised by a different danger of fire activation or in other words by a different probability of severe fire p_1.

Type of building Occupancy	Danger of fire activation	p_1 [10^{-7}/year . m²]	$\frac{(p_1)}{(p_{1\,normal})}$
Museum, Art gallery	Low	0,4	10^{-1}
Hotel, School, Office	Normal	4	1
Machine Works	Average	40	10
Paint Workshop Chemistry Laboratory	High	400	100
Paint Factory Fireworks Industry	Ultra-High	4000	1000

TABLE 5.11 : Influence of the risk of fire activation

The γ_{qf} for the different building occupancies are given on the Figure 5.6

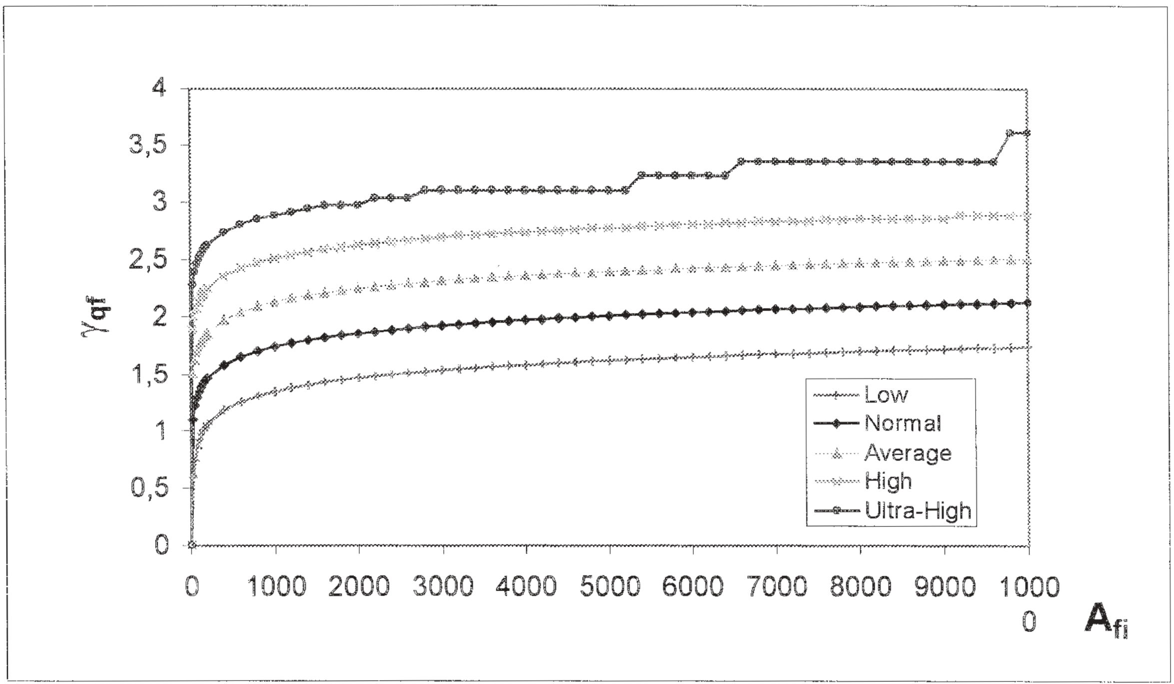


FIGURE 5.6: γ_{qf} for different building occupancies as a function of A_{fi}

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 (Machine Works). For each class, it is possible to deduce an additional coefficient γ_{q2} which is the ratio between the γ_{qf} of that class and the γ_{qf} for a **normal** danger of fire activation noted also γ_{q1} (see Figure 5.6)

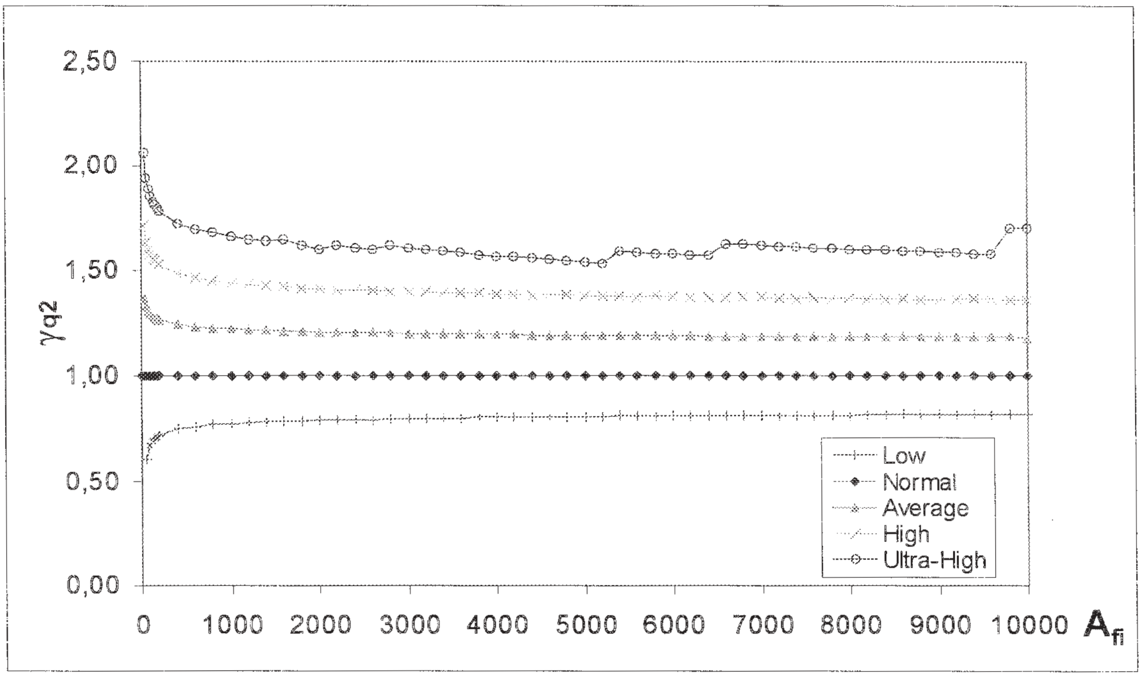


FIGURE 5.7: Differentiation factor γ_{q2} for different building occupancies as a function of A_{fi}

In that way, the γ_{qf} factor can be obtained by multiplying the γ_{q1} factor of Table 5.11 and the γ_{q2} factor of the following Table 5.12 corresponding to an area of 1000 m^2.

Type of building Occupancy	γ_{q2}			
A_{fi} [m^2]→	**100**	**200**	**1.000**	**10.000**
Museum, Art gallery	0,68	0,72	0,78	0,82
Hotel, School, Office	1	1	1	1
Machine Works	1,29	1,26	1,22	1,18
Paint Workshop Chemistry Laboratory	1,57	1,52	1,44	1,36
Paint Factory Fireworks Industry	1,85	1,78	1,66	1,70

TABLE 5.12 : Differentiation factor γ_{q2} - Influence of the danger of fire activation

ACTIVE FIRE SAFETY MEASURES

In the same way, the influence of active fire fighting measures can be quantified. Each active measure reduces the probability that a starting fire is developing and turns to flash-over or a fully engulfed compartment. Therefore, the probability of severe fire $p_{fi,AM}$ in case of Active Measures (AM) is equal to the probability p_{fi} without active measure multiplied by p_2 and eventually p_3 or p_4 of Tables 5.2 to 5.4.

In case of detection by smoke (p_3 = 0,0625) or heat (p_3 = 0,25), the curve of Figure 5.5 becomes the following Figures 5.8a and 5.8b.

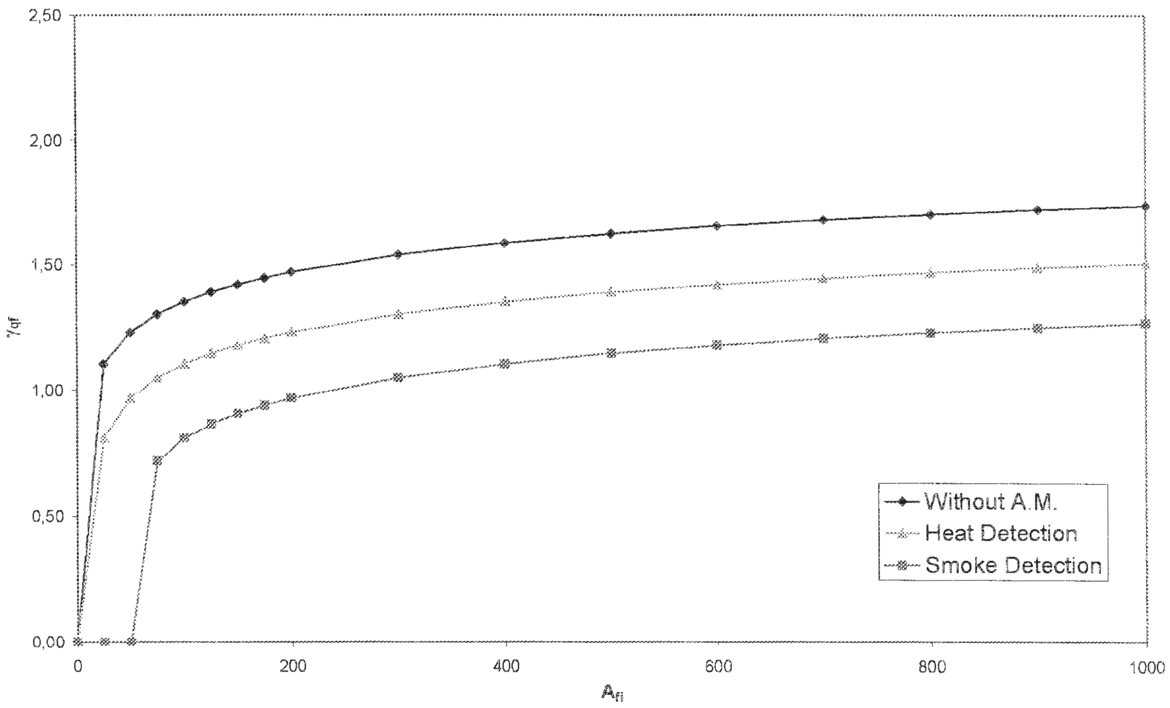


FIGURE 5.8a: γ_{qf} **in case of detection for** A_{fi} **[0-1000]**

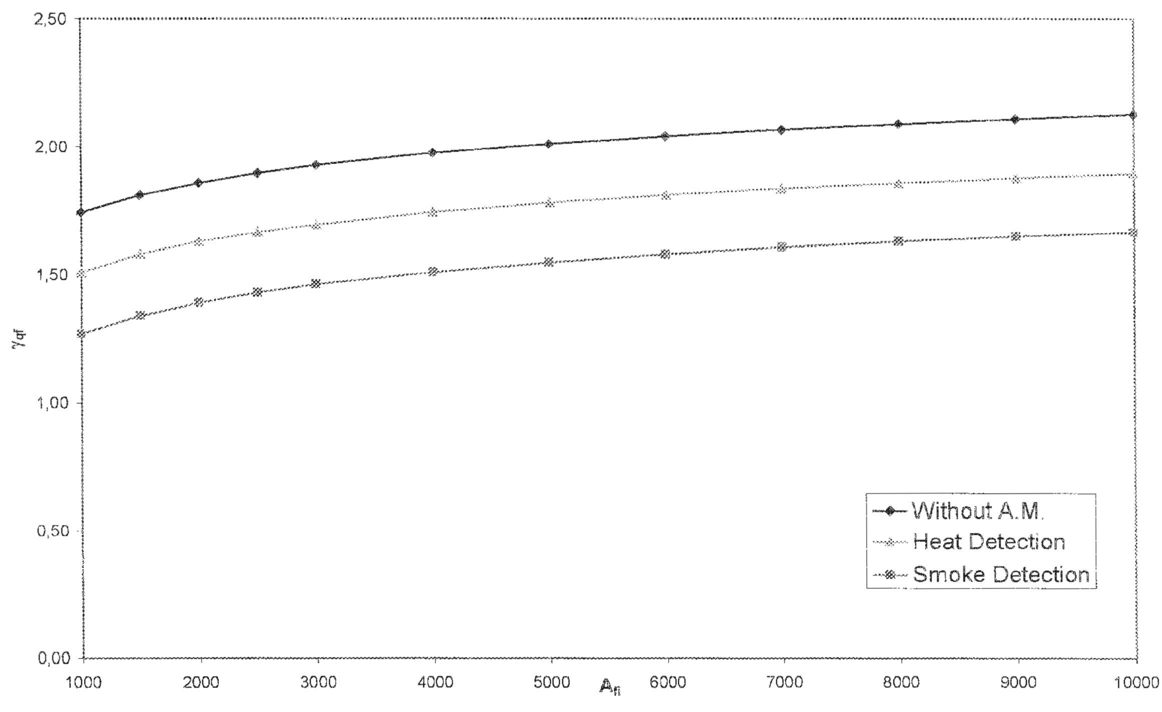


FIGURE 5.8b: γ_{qf} **in case of detection for** A_{fi} **[1000-10000]**

It is then possible to deduce an additional coefficient γ_{ni} which is the ratio between the γ_{qf} with detection and the γ_{qf} without detection (see Figures 5.9a and 5.9b).

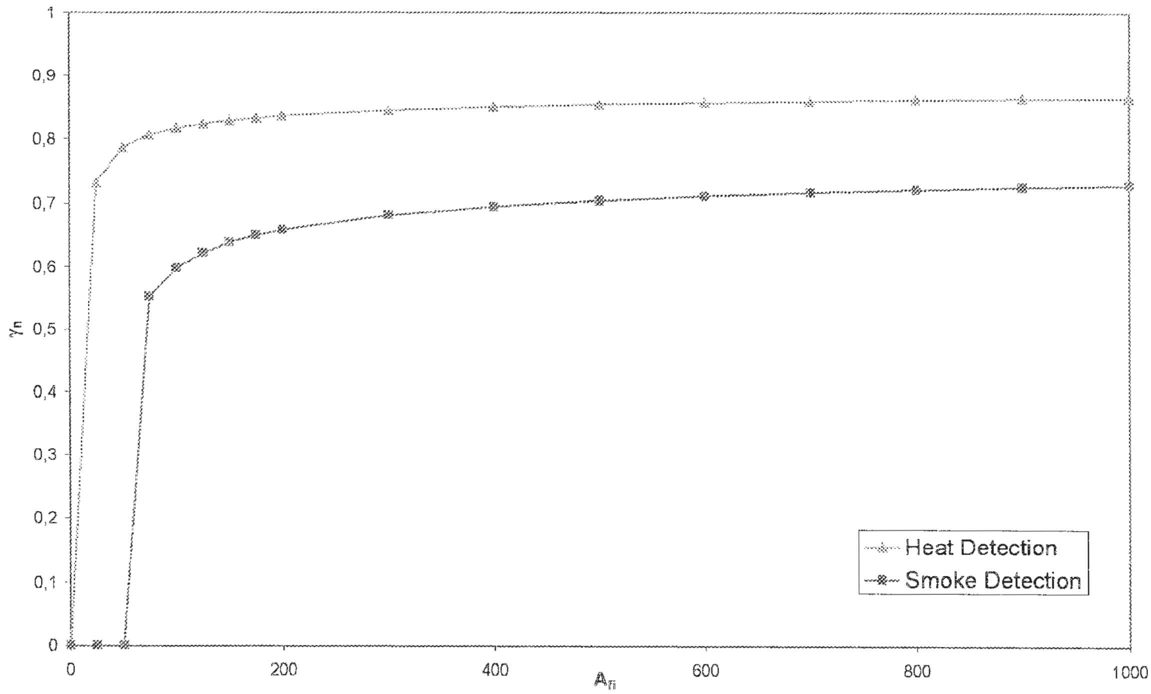


FIGURE 5.9a: γ_n in case of detection for A_{fi} [0-1000]

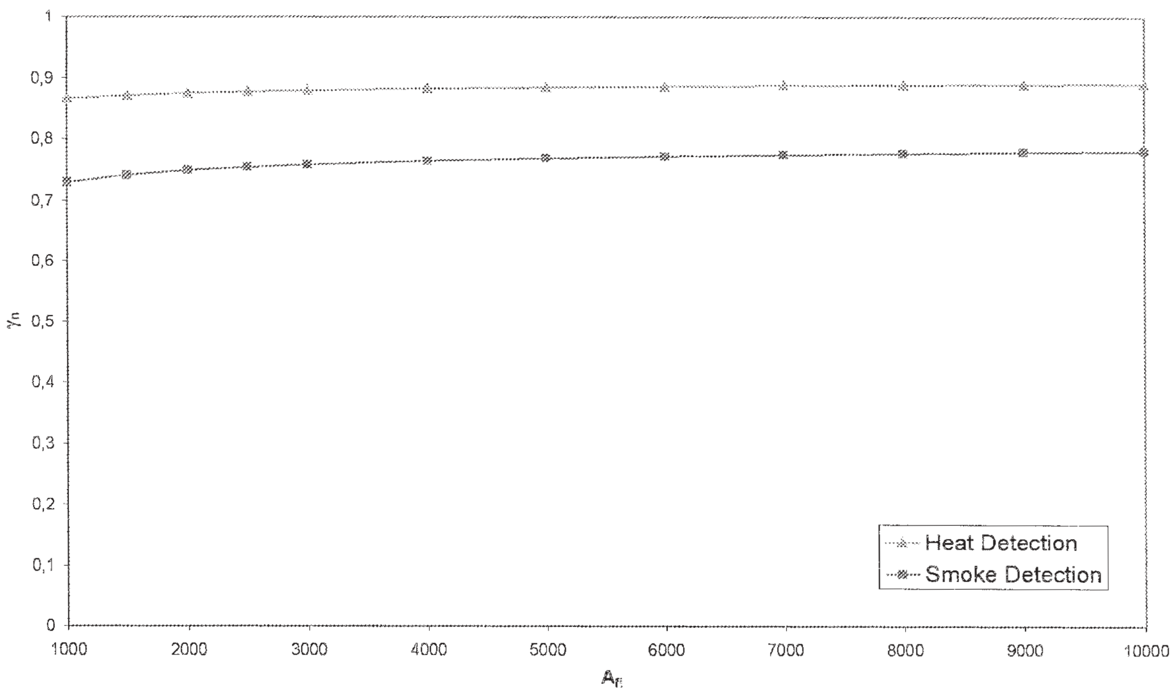


FIGURE 5.9b: γ_n in case of detection for A_{fi} [1000-10000]

In the same manner, the effect of

- a sprinkler system ($p_4 = 0{,}02$)
- a sprinkler system with 1 or 2 additionnal water supplies ($p_4 = 0{,}01$ or $0{,}005$)
- a detection system by heat ($p_3 = 0{,}25$)
- a detection system by smoke ($p_3 = 0{,}0625$)
- an automatic alarm transmission ($p_3 = 0{,}25$)
- a work firemen team ($p_2 = 0{,}02$)
- the Off Site firemen ($p_2 = 0{,}1$)

may be considered by using corresponding γ_{ni} factors.

These γ_{ni} factors are given in table 5.13. They depends on the area A_{fi} but the values given in table 5.14 and corresponding to 1.000 m² can be adopted in case of simplified calculation. Up to an area A_{fi} of 10.000 m², this simplified method is never more than 5% unsafe if at least two active fighting measures are used.

GAMMAn

Afi [m2]	Sprinkler	Sprinkler 1Wat. Suply	Sprinkler 2 Wat. Suply	Detect. by heat	Detect. By smoke	Work Firemen	Off Site Firemen	Off Site Firemen Detect. by heat	Off Site Firemen Detect. By smoke	Off Site Firemen Detect. by heat Autom. Transm.	Off Site Firemen Detect. By smoke Autom. Transm.	Sprinkler Off Site Firemen Detect. by heat	Sprinkler Off Site Firemen Detect. By smoke	Sprinkler Off Site Firemen Detect. by heat Autom. Transm.	Sprinkler Off Site Firemen Detect. By smoke Autom. Transm.
Probability of failure of the Active measures	0,02	0,02 0,5	0,02 0,25	0,25	0,0625	0,02	0,1	0,1 0,25	0,1 0,0625	0,1 0,25 0,25	0,1 0,0625 0,25	0,02 0,1 0,25	0,02 0,1 0,0625	0,02 0,1 0,25 0,25	0,02 0,1 0,0625 0,25
→	0,02	0,01	0,005	0,25	0,0625	0,02	0,1	0,025	0,00625	0,00625	0,0015625	0,0005	0,000125	0,000125	0,00003125
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0,731385801	0	0	0	0	0	0	0	0	0	0	0
50	0	0	0	0,787118131	0	0	0,602602345	0	0	0	0	0	0	0	0
75	0	0	0	0,806192398	0,552480138	0	0,656320759	0	0	0	0	0	0	0	0
100	0	0	0	0,81683585	0,597422142	0	0,681187625	0	0	0	0	0	0	0	0
125	0	0	0	0,823945161	0,621649924	0	0,696558292	0	0	0	0	0	0	0	0
150	0	0	0	0,829172197	0,637673187	0	0,707363239	0,433904843	0	0	0	0	0	0	0
175	0,38803289	0	0	0,833245278	0,649379104	0,388032888	0,715541809	0,478609563	0	0	0	0	0	0	0
200	0,44401519	0	0	0,836552975	0,658466014	0,444015187	0,722042464	0,504108784	0	0	0	0	0	0	0
225	0,47229023	0	0	0,839320897	0,665816932	0,472290226	0,727392757	0,521845477	0	0	0	0	0	0	0
250	0,49143352	0	0	0,841685028	0,671939914	0,491433517	0,731907105	0,535306464	0	0	0	0	0	0	0
275	0,50582472	0	0	0,843740732	0,677155716	0,505824724	0,735791334	0,546060879	0	0	0	0	0	0	0
300	0,51727745	0	0	0,845550895	0,681676703	0,517277447	0,73918618	0,554952605	0	0	0	0	0	0	0
325	0,52673868	0	0	0,847172982	0,685658107	0,526738675	0,742198135	0,56249591	0	0	0	0	0	0	0
350	0,53475382	0,358865831	0	0,848628471	0,689197059	0,534753823	0,744889598	0,569010655	0	0	0	0	0	0	0
375	0,54168103	0,391072143	0	0,84995085	0,692377281	0,541681031	0,747320879	0,574725598	0	0	0	0	0	0	0
400	0,54776081	0,411177898	0	0,851162735	0,695260236	0,547760809	0,749534688	0,579801522	0	0	0	0	0	0	0
425	0,55316046	0,426030265	0	0,852275434	0,697889753	0,553160456	0,751561678	0,584353293	0	0	0	0	0	0	0
450	0,55800724	0,437846296	0	0,853306562	0,700305292	0,558007244	0,753429666	0,588472204	0	0	0	0	0	0	0
475	0,56239213	0,447654305	0	0,854260814	0,7025331	0,562392131	0,755157912	0,592223684	0	0	0	0	0	0	0
500	0,56639219	0,456030724	0	0,855156765	0,704602279	0,566392186	0,756768918	0,595666536	0	0	0	0	0	0	0
525	0,57005973	0,463326746	0	0,855990835	0,706527501	0,570059734	0,758270068	0,598838928	0	0	0	0	0	0	0
550	0,5734448	0,469781563	0	0,85677768	0,708329731	0,573444799	0,759679381	0,601780238	0,329368287	0,329368287	0	0	0	0	0
575	0,57658068	0,475557933	0	0,857518604	0,710019039	0,576580684	0,761001406	0,604515118	0,355433462	0,355433462	0	0	0	0	0
600	0,57949766	0,480777253	0	0,858212864	0,711606246	0,579497663	0,762246069	0,607068231	0,372382718	0,372382718	0	0	0	0	0
625	0,58222604	0,485534665	0	0,858875609	0,713107375	0,582226041	0,76342672	0,609464191	0,385204841	0,385204841	0	0	0	0	0
650	0,58478457	0,489898597	0	0,859506276	0,714527626	0,584784574	0,764545907	0,611717236	0,395592657	0,395592657	0	0	0	0	0
675	0,58719312	0,493926737	0,305226436	0,860108942	0,715878175	0,587193119	0,765611455	0,613844621	0,404351605	0,404351605	0	0	0	0	0
700	0,58946255	0,497659718	0,333972494	0,860680896	0,717158293	0,589462546	0,76662224	0,615853166	0,411930107	0,411930107	0	0	0	0	0
725	0,59160677	0,501134907	0,351323259	0,86122405	0,718374963	0,591606773	0,767583358	0,617754519	0,418609986	0,418609986	0	0	0	0	0
750	0,59363664	0,504381855	0,364143623	0,861738092	0,719532574	0,593636639	0,768499012	0,619558061	0,42458044	0,42458044	0	0	0	0	0
775	0,595574	0,507436074	0,374431965	0,862245488	0,720650872	0,595573998	0,769386773	0,621283561	0,429983575	0,429983575	0	0	0	0	0
800	0,59741377	0,510307161	0,383063231	0,862725516	0,721715597	0,597413765	0,770230781	0,622924457	0,434907511	0,434907511	0	0	0	0	0
825	0,59916796	0,513016702	0,390518116	0,863184797	0,722735385	0,599167963	0,771041597	0,624491753	0,439430339	0,439430339	0	0	0	0	0
850	0,60084745	0,515584069	0,397089877	0,863632252	0,723719908	0,600847447	0,771824871	0,625994751	0,443612972	0,443612972	0	0	0	0	0
875	0,6024493	0,518014977	0,402964569	0,864058571	0,724659909	0,602449301	0,772572981	0,627430076	0,447495091	0,447495091	0	0	0	0	0
900	0,60398235	0,520323981	0,408277724	0,864463632	0,725562391	0,60398235	0,773290643	0,628804584	0,451116436	0,451116436	0	0	0	0	0
925	0,6054609	0,5225297	0,413133359	0,864870095	0,726440244	0,605460896	0,773991801	0,630133502	0,45451469	0,45451469	0	0	0	0	0
950	0,60687268	0,524626794	0,417593757	0,865245904	0,727277575	0,606872685	0,77465772	0,631402414	0,457703251	0,457703251	0	0	0	0	0
975	0,608244	0,526642502	0,421730696	0,865627496	0,728100874	0,608243996	0,775317779	0,632637756	0,460720235	0,460720235	0	0	0	0	0
1000	**0,60955443**	**0,5285635**	**0,425572955**	**0,865982762**	**0,728884725**	**0,609554434**	**0,775944073**	0,633818936	0,46356617	0,46356617	0	0	0	0	0
2000	0,64068789	0,571543717	0,495603232	0,875017777	0,748277372	0,64068789	0,79156524	0,662186256	0,521218808	0,521218808	0	0	0	0	0
3000	0,65571633	0,591010253	0,522225788	0,879706125	0,758076278	0,655716332	0,799541805	0,676053288	0,545029021	0,545029021	0,373506014	0	0	0	0
4000	0,6653403	0,603191764	0,538094239	0,882766508	0,764460579	0,665340302	0,804754968	0,68497744	0,559514129	0,559514129	0,409220689	0	0	0	0
5000	0,67233787	0,611928048	0,549189679	0,885045718	0,769161359	0,672337875	0,808606213	0,691485073	0,56974578	0,56974578	0,429861643	0	0	0	0
6000	0,67775195	0,61864049	0,557593054	0,886805785	0,772815428	0,677751954	0,811602072	0,696527339	0,577541104	0,577541104	0,444156809	0	0	0	0
7000	0,68217868	0,624088293	0,564332578	0,888296377	0,775826607	0,682178675	0,814075382	0,700659129	0,583820911	0,583820911	0,454993398	0,271878786	0	0	0
8000	0,68587632	0,628622007	0,569903276	0,88951779	0,778343879	0,685876324	0,816147604	0,704111363	0,589026455	0,589026455	0,463633402	0,312636139	0	0	0
9000	0,68910106	0,63254768	0,574681522	0,890619439	0,780571773	0,689101061	0,817994741	0,707126705	0,59350622	0,59350622	0,470816933	0,333969031	0	0	0
10000	0,69183285	0,635889781	0,578754831	0,891491296	0,782425361	0,691832853	0,819504657	0,709676907	0,597324427	0,597324427	0,476860239	0,348759018	0	0	0

TABLE 5.13

Active Fire Safety Measure	γ_{ni}			
A_{fi} [m²]→	**200**	**500**	**1.000**	**10.000**
Sprinkler	0,44	0,57	0,61	0,69
Sprinkler with one water supply	0	0,46	0,53	0,64
Sprinkler with two water supply	0	0	0,43	0,58
Automatic fire detection	By heat: 0,84 by smoke: 0,66	by heat: 0,86 by smoke: 0,70	by heat: 0,87 by smoke: 0,73	by heat: 0,89 by smoke: 0,78
Automatic Alarm Transmission	0,84	0,86	0,87	0,89
Work Firemen	0,44	0,57	0,61	0,69
Off site fire brigade see (⁎)	0,72	0,76	0,78	0,82

(⁎) This corresponds to professional Fire Brigade with intervention time between 10' and 20' ; see tables 5.3 and 5.15

TABLE 5.14: Differentiation factor γ_n - Influence of active fire safety measures.

	Time between Alarm and Action of the FIREMEN		
	≤ 10'	10' < t ≤ 20'	20' < t ≤ 30'
Type of FIREMEN	γ_{OFB}		
Professional	0,71	0,78	0,84
Not-Professional	0,78	0,84	1

TABLE 5.15 : Differentiation factor γ_{OFB}

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 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 the staircases. For these normal fire fighting measures, the γ_{ni} is 1,0 but becomes 1,5 if they have not been foreseen (see Table 5.16).

TABLE 5.16

Official Document: Title	Date of publication	Automatic Fire Suppression: Automatic Water Extinguishing System γ_{n1}	Automatic Fire Suppression: Independent Water Supplies 0 | 1 | 2 γ_{n2}	Automatic Fire Detection: Automatic fire Detection & Alarm by Heat γ_{n3}	Automatic Fire Detection: Automatic fire Detection & Alarm by Smoke γ_{n4}	Automatic Fire Detection: Automatic Alarm Transmission to Fire Brigade γ_{n5}	Manual Fire Suppression: Work Fire Brigade γ_{n6}	Manual Fire Suppression: Off Site Fire Brigade γ_{n7}	Manual Fire Suppression: Safe Access Routes γ_{n8}	Manual Fire Suppression: Fire Fighting Devices γ_{n9}	Manual Fire Suppression: Smoke Exhaust System γ_{n10}	$\gamma_n^{min} = \gamma_{n1} \cdots \gamma_{n10}$ / $\gamma_n^{max} = \gamma_{n4} \cdot \gamma_{n7}$
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.

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 by using the Tables 5.1 to 5.5.

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

$$\beta_{fi,t} = \phi^{-1}\left(\frac{p_t}{p_{fi}}\right) = \phi^{-1}\left(\frac{7{,}23 . 10^{-5}}{p_{fi}}\right)$$

with $p_{fi} = p_1 . p_2 . p_{n1} ... p_{ni}$,

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

The whole procedure for A_{fi} up to 10.000 m² is given on tables 5.6 to 5.9.

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

For a compartment, the Tables 5.10, 5.12 and 5.14 enable to find the γ_{q1}, γ_{q2} and γ_{ni} . The global factor γ_{qf} is equal to $\gamma_{q1} . \gamma_{q2} . \gamma_{n1} .... \gamma_{ni}$.

- **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 tools presented in chapters 6 and 7.

6 FIRE DEVELOPMENT CALCULATIONS

INTRODUCTION

When simulating numerically the fire development, different simplifications of the fire dynamics can be made.

The present chapter will explain the models to apply in pre-flashover situation (the models of localised fire and 2 zone models) and in post-flashover situation (fully-engulfed fire).

The field Models (CFD: Computer Fluid Dynamics) are excluded in this chapter. They are too complex and time consuming to be used as a simple tool.

6.1 LOCALISED FIRE

In a localised fire, there is an accumulation of combustion products in a layer beneath the ceiling (upper layer), with a horizontal interface between this hot layer and the lower layer where the temperature of the gases remains much colder.

This situation is well represented by a two zone model, useful for all pre-flashover conditions. Besides calculating the evolution of gas temperature, these models are used in order to know the smoke propagation in buildings and to estimate the life safety as a function of smoke layer height, toxic gases concentration, radiative flux and optical density.

The thermal action on horizontal elements located above the fire also depends on their distance from the fire. It can be assessed by specific models for the evaluation of the local effect on adjacent elements, such as Hasemi's method.

6.1.1 TWO ZONE MODELS

Zone model 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 for each zone of the compartment. They are based on the fundamental hypothesis that the temperature is uniform in each zone.

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.

The data which have to be provided to a zone model are:

- geometrical data, such as the dimensions of the compartment, the openings and the partitions;
- material properties of the walls;
- fire data, as RHR curve, pyrolisis rate, combustion heat of fuel.

In a two zone model the equations expressing the equilibrium of mass and of energy are written for each of the two layers and exchanges between the two layers are considered.

As a result of the simulation, the 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 products, is very important to assess the tenability of the compartment for the occupants. Figure 6.1 shows how a compartment is modelled by a two zone model, with different terms of the energy and mass balance represented.

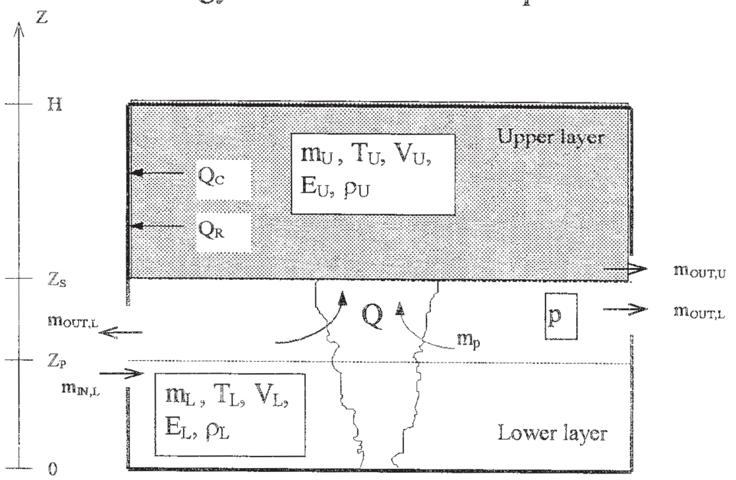


FIGURE 6.1: a compartment in a two zone model

Figure 6.1 is typical of a simple situation where the compartment exchanges mass and energy only with the outside environment. These kind of models have 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 threat to life. Such a situation, analysed by multi-compartment two zone models, is depicted on Figure 6.2.

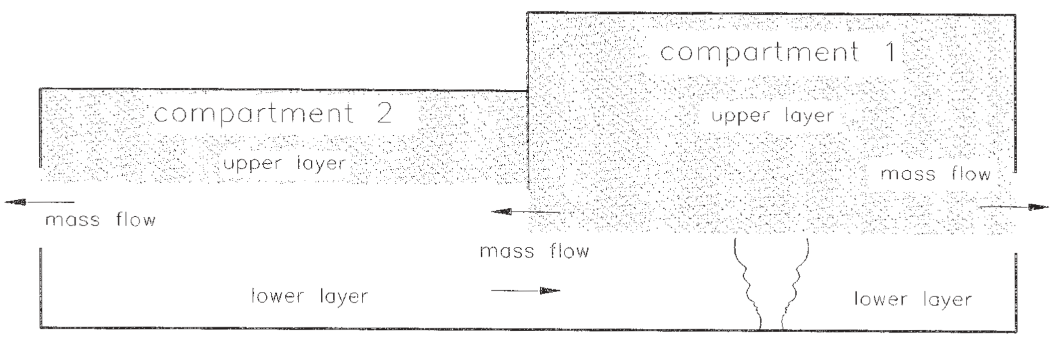


FIGURE 6.2: a compartment in a multi-compartment two zone model

6.1.2 HASEMI'S METHOD

Hasemi's method is a simple tool for the evaluation of the localised effect on horizontal elements located above the fire. It is based on the results of tests made at the Building Research Institute in Tsukuba, Japan [-].

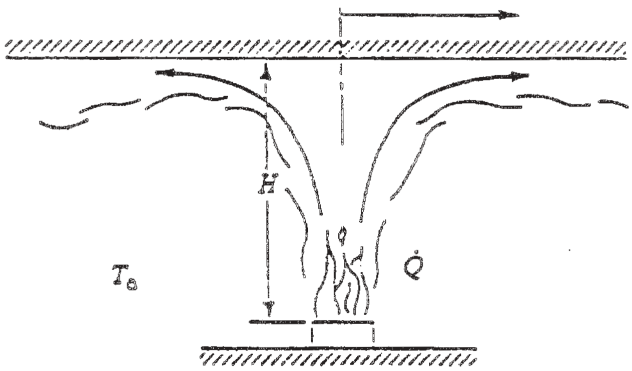


FIGURE 6.3: localised fire scheme

The data for the application of the method are:

- Q Rate of the Heat Release of the fire [W]
- H_f height between floor and ceiling [m]
- D diameter (or characteristic length) of the fire [m]
- H_s vertical distance between the floor and the seat of the fire source [m]

The variables are:

- H distance between the fire source and the ceiling [m]
- Q^* non dimensional Rate of Heat Release [-]
- Q_H^* non dimensional Rate of Heat Release [-]
- z' vertical position of the virtual heat source, with respect to the seat of the fire source [m]
- L_H horizontal length of the flame on the ceiling [m]
- r horizontal distance, at the ceiling, from the centre of the fire [m]

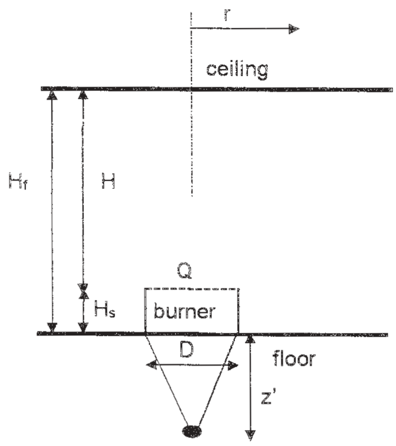


FIGURE 6.4: Hasemi fire description

The procedure is:

Calculate H $$\mathbf{H = H_f - H_s} \quad (6.1)$$

Calculate Q^* $$\mathbf{Q^* = \frac{Q}{1{,}11\times10^6\, D^{2,5}}} \quad (6.2)$$

Calculate Q_H^* $$\mathbf{Q_H^* = \frac{Q}{1{,}11\times10^6\, H^{2,5}}} \quad (6.3)$$

Calculate z' $$\mathbf{z' = 2{,}4\, D\left(Q^{*\,2/5} - Q^{*\,2/3}\right)} \qquad Q^* < 1{,}00 \quad (6.4)$$

$$\mathbf{z' = 2{,}4\, D\left(1{,}00 - Q^{*\,2/5}\right)} \qquad Q^* \geq 1{,}00 \quad (6.5)$$

Calculate $(L_H+H)/H$ $$\mathbf{\frac{L_H + H}{H} = 2{,}90\, Q_H^{*\,0,33}} \quad (6.6)$$

Calculate L_H from the value calculated in the previous equation and from the value of H

Calculate the value of the flux q'' in [kW/m^2] at a distance r, according to

$$\mathbf{q'' = 100} \qquad y < 0{,}30 \quad (6.7)$$
$$\mathbf{q'' = 136{,}30 - 121{,}00\, y} \qquad 0{,}30 < y < 1{,}00 \quad (6.8)$$
$$\mathbf{q'' = 15\, y^{-3,7}} \qquad y > 1{,}00 \quad (6.9)$$

where $$\mathbf{y = \frac{r + H + z'}{L_H + H + z'}} \quad (6.10)$$

The flux q'' received by the ceiling decreases as a function of the ratio y and increases as a function of Q. In the Figure 6.5 these functions are shown for the case:

r = 0 H = 5 m D = 3 m

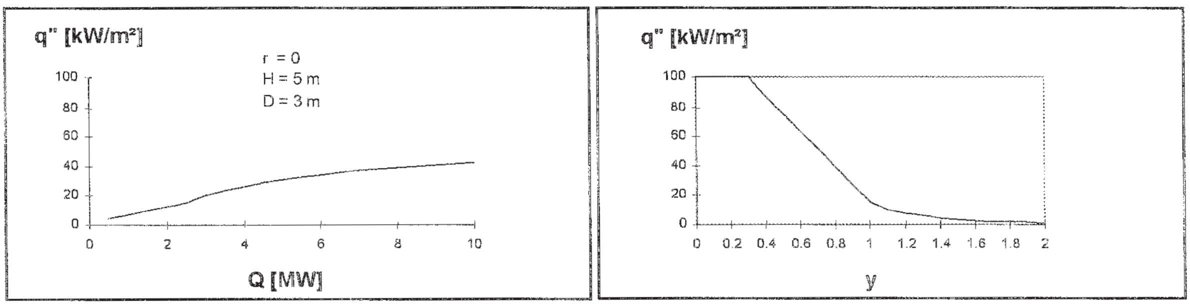


FIGURE 6.5: q" as a function of y and Q

6.1.3 COMBINATION BETWEEN 2 ZONE MODEL AND LOCALISED FIRE MODEL

In a localised fire the gas temperature distribution in the compartment may be estimated by a 2 zone model. In this model the gas temperature in each layer is calculated with the hypothesis that it is uniform in each layer. This average temperature in the hot zone is generally sufficiently accurate as far as global phenomena are considered: quantity of smoke to be extracted from the compartment, likelihood of flashover, total collapse of the roof or ceiling, etc.

When it comes to estimating the local behaviour of a structural element located just above the fire, the hypothesis of a uniform temperature may be unsafe and the two zone model has to be combined with the localised fire formula given at the 6.1.2 paragraph.

The temperatures close to the beam are obtained by – for each point alongside the beam – taking the highest temperature predicted by each of the models.

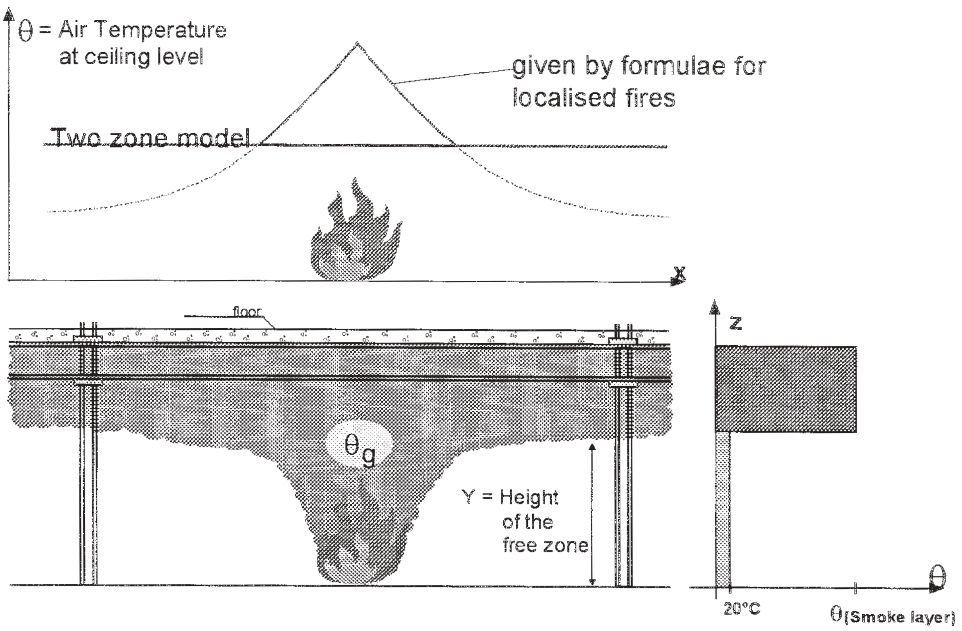


FIGURE 6.6

The height of the smoke zone and the temperatures of the hot gases at the level of the steel structures at different distances from the fire can be calculated by the model TEFINAF [20]. This model combines a two zone model which provides the height and the mean temperature of the hot zone and the localised fire formula which gives the temperature peak just above the fire and at different distances from the fire.

6.2 FULLY ENGULFED FIRE

To model a fully engulfed fire within a building there are several types of models. Some of the most widely used are described in this chapter.
The natural fire concept is an alternative to the nominal fires defined in prescriptive codes (ISO, ASTM, hydrocarbon curves...). Thus, the nominal fires will not be included in this description.
Also the field models (CFD) are not included in this chapter. They are too complex and need too much time and data in order to use them as a simple engineering tool.

6.2.1 PARAMETRIC FIRES

Parametric fires provide a simple means 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 reality. In almost every parametric fire which can be found in the literature, the parameters taken into account, in one way or another, are:

- the geometry of the compartment
- the fire load within the compartment,
- the openings within the walls and/or in the roof and
- the type and nature of the different construction elements forming the boundaries 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 moderate dimensions. They nevertheless constitute 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 [2] for such a parametric fire. It is valid for compartments up to 100 m^2 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. (O and b are defined here below).

Some corrections have been made to improve this proposal. 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 which takes into account the large mass flow through opening in case of fuel controlled fires.

This new formulation of the parametric fire is now presented and is valid for any b.

The evolution of the gas temperature within the compartment is given by :

$$\Theta_g = 1.325\left(1 - 0,324e^{-0,2t^*} - 0,204e^{-1,7t^*} - 0,472e^{-19t^*}\right) + 20°\,C \qquad (6.11)$$

with

$$t^* = \Gamma t \qquad (6.12)$$

$$\Gamma = \frac{(O/0,04)^2}{(b/1.160)^2} \qquad (6.13)$$

$$O = A_v \sqrt{h}/A_t \qquad (6.14)$$

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,

b is the so-called b-factor in [J/m²s$^{1/2}$K]. It is function of the thermal inertia of boundaries (see § 3.3 for b calculation).

The duration of the heating phase is determined by:

$$t_d = \max\left(0,13\times10^{-3}\, q_{t,d}/O\, ;\, t_{lim}\right) \qquad [\text{hour}] \qquad (6.15)$$

with: $q_{t,d}$ design value of the fire load density related to A_t, in MJ/m²,

t_{lim} 20 minutes, similar to the free burning fire duration assumed in Annex C of Eurocode 1-2-2 [2].

When applying equation 6.15, two different possibilities exist:

- Either 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 larger than the chosen limit time t_{lim}, in which case equations 6.11 to 6.14 and equations 6.21 to 6.23 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 6.11 to 6.14 are applied with a modified opening factor, O_{lim}, calculated as the one leading to the chosen limit time from the following equation:

  $$O_{lim} = 0,13\times10^{-3}\, q_{t,d}/t_{lim} \qquad (6.16)$$

  Equation 6.15 and 6.16 are modified in the following way:

  $$t^*_{lim} = \Gamma_{lim}\, t \qquad (6.17)$$

$$\Gamma_{lim} = \frac{(O_{lim}/0{,}04)^2}{(b/1.160)^2} \tag{6.18}$$

and t^*_{lim} is used in equation 6.11 instead of t^*.

A last, in order to take the effect of the ventilation during the heating phase, in the case of $t_d = t_{lim}$:

If $O > 0{,}04$ **and** $q_{t,d} < 75$ **and** $b < 1.160$

$$\textbf{then}\quad k = 1 + \left(\frac{O - 0{,}04}{0{,}04}\right)\left(\frac{q_{t,d} - 75}{75}\right)\left(\frac{1.160 - b}{1.160}\right) \tag{6.19}$$

$$\textbf{and}\quad \Gamma_{lim} = k\,\frac{(O_{lim}/0{,}04)^2}{(b/1.160)^2} \tag{6.20}$$

The temperature-time curve during the cooling phase is given by:

$$\Theta_g = \Theta_{max} - 625\left(t - t^*_d\right) \quad \text{for} \quad t^*_d \le 0{,}5 \tag{6.21}$$

$$\Theta_g = \Theta_{max} - 250\left(3 - t^*_d\right)\left(t - t^*_d\right) \quad \text{for} \quad 0{,}5 \le t^*_d \le 2{,}0 \tag{6.22}$$

$$\Theta_g = \Theta_{max} - 250\left(t - t^*_d\right) \quad \text{for} \quad 2{,}0 \le t^*_d \tag{6.23}$$

with θ_{max} maximum temperature at the end of the heating phase.

An example of results (fire load $q_{t,d}$ = 180 MJ/m^2, b = 1.160 J/m^{2}s$^{1/2}$K, opening factor O from 0,04 m$^{1/2}$ to 0,20 m$^{1/2}$) is shown on Figure 6.7.

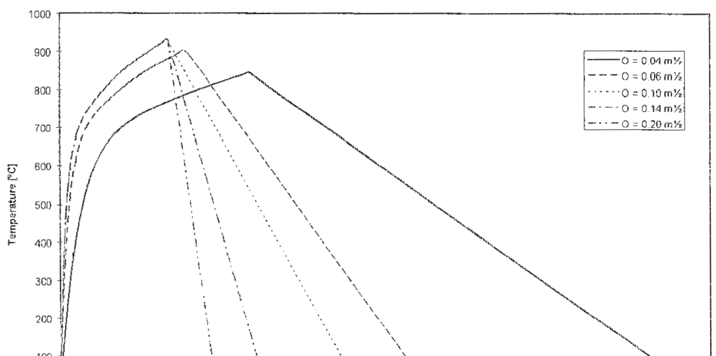


FIGURE 6.7: example of parametric fires

With the modified parametric fire the comparison has been made between the results of tests and the results of the improved predictions. Figure 6.8 concerns the maximum temperature in the gas. The coefficient of correlation, which had the value of 0,19 with the previous Eurocode formula, has now a value of 0,83.

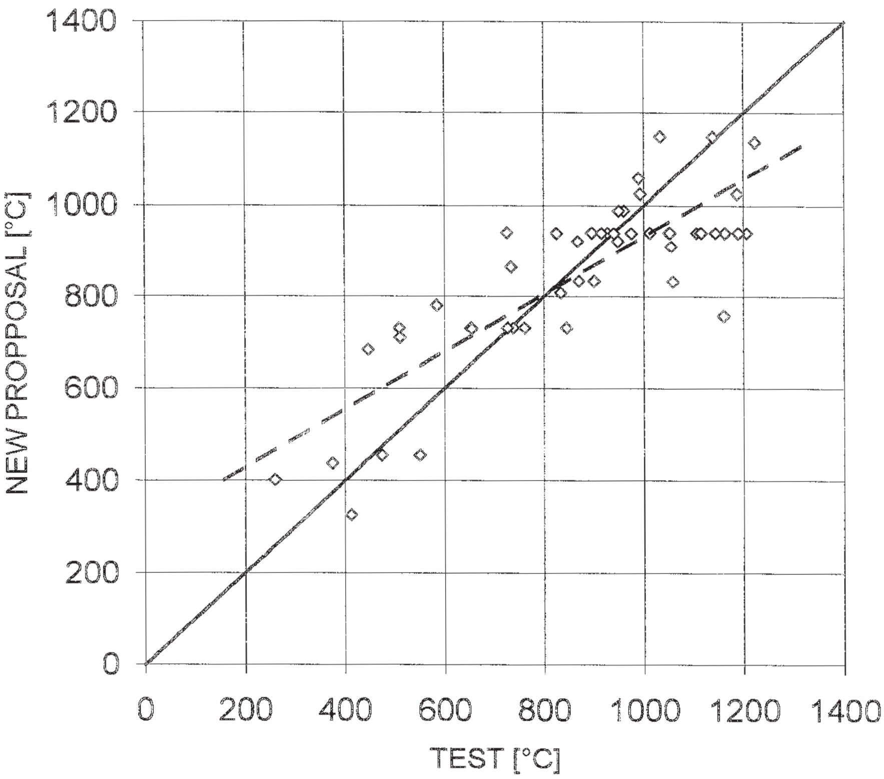


FIGURE 6.8: maximum gas temperature in the compartment

6.2.2 ZONE MODELS

Zone models have been already introduced in the chapter 6.1.1, where a short description of a two zone model was presented. The application field of a two zone model is the pre-flashover phase of the fire. For a fully engulfed fire a one zone model should be used.

6.2.2.1 ONE ZONE MODEL

The one zone model is based on the fundamental hypothesis that, during the fire, the gas temperature is uniform in the compartment. One zone models are valid for post-flashover conditions.

The data have to be supplied with a higher degree of detail than for the parametric curves and are the same as those required for a two zone model.

Figure 6.9 shows how a compartment fire is modelled, with different terms of the energy and mass balance represented.

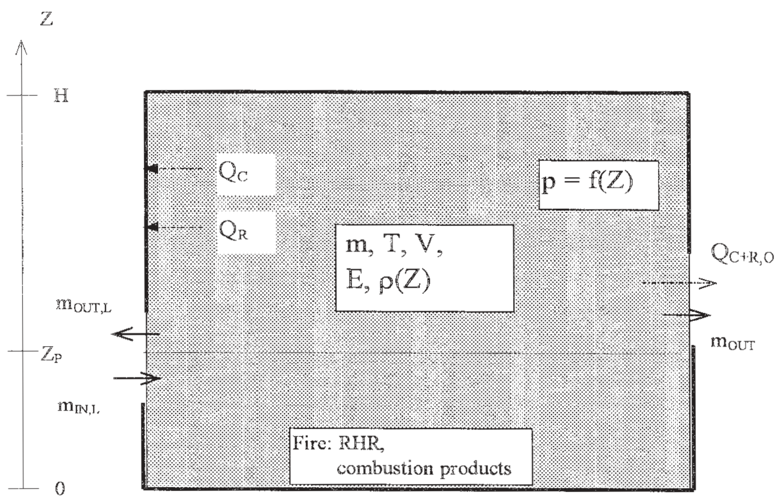


FIGURE 6.9: a compartment in a one zone model

During the Working Group 1 activities of this Research Project the one zone model, OZone, has been developed at University of Liège.

This model has been validated taking as reference the results of 54 experimental tests. Figures 6.10 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 points giving a perfect fit. The dotted line is the linear regression among all points.

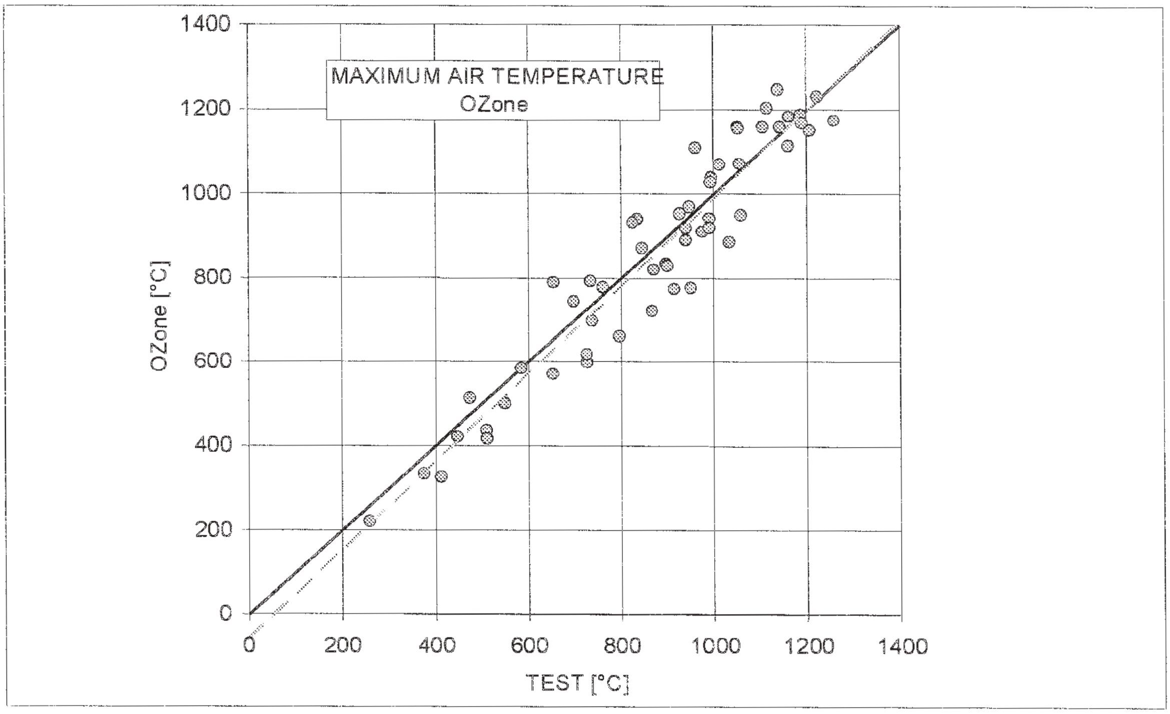


FIGURE 6.10: maximum gas temperature in the compartment

Another comparison is represented in Figure 6.11. For each test, the temperature evolution was computed in a typical unprotected steel section - HEB 200, U/F = 147 m^{-1} - first submitted to the recorded gas temperature, then submitted to the computed gas temperature. This allowed to draw the graph where each test is represented by the maximum temperature in the unprotected steel section.

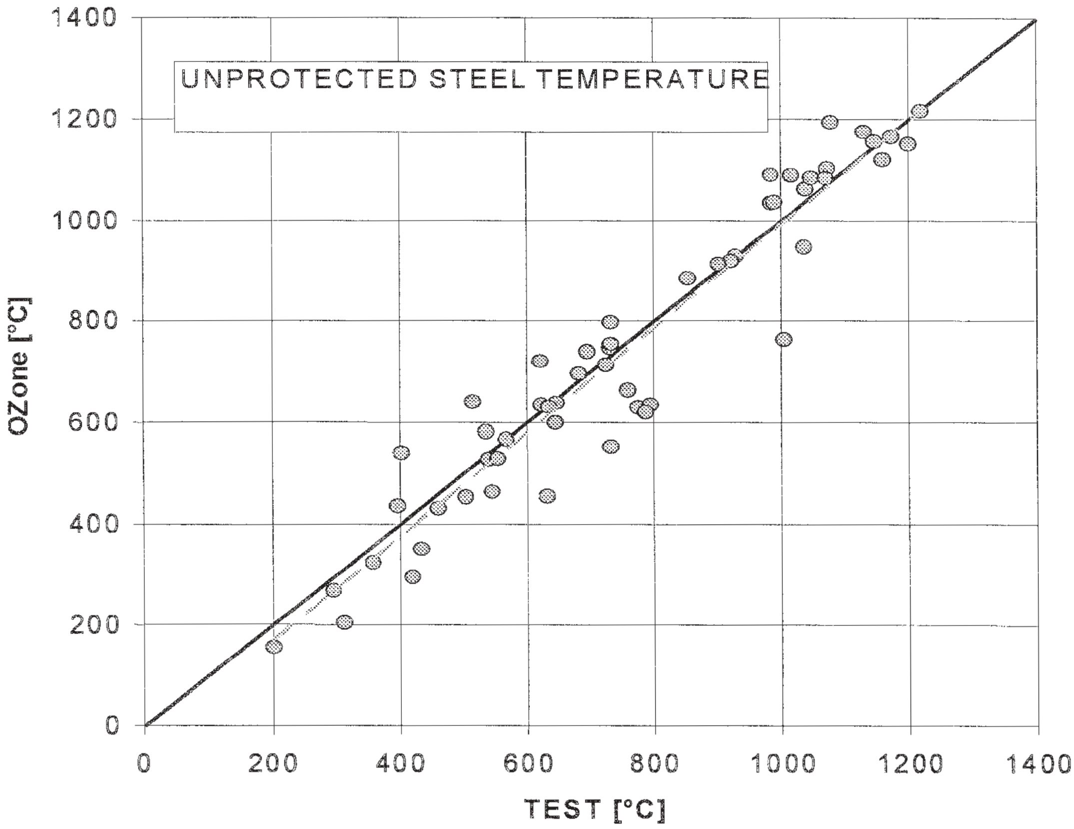


FIGURE 6.11: maximum temperature in the unprotected steel section

6.3 COMBINATION OF 1-ZONE AND 2-ZONES MODELS. CHOICE OF THE MODEL

After having defined the fire characteristics, i.e. RHR curve, compartment geometry, wall characteristics, it is necessary to choose the natural fire model to apply according to the considered scenario. This choice will be made in accordance with the application domain of the models.

In this consideration, it is assumed that the first application has to be a "two zone model" application. The question is how and when the transition from the "two zone model" application to a "one zone model" application occurs.

The results of a "two zone model" are given in the 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 (see figure 6.14). 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) is such that the combustible material is 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 lead 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 indicated in Figure 6.12.

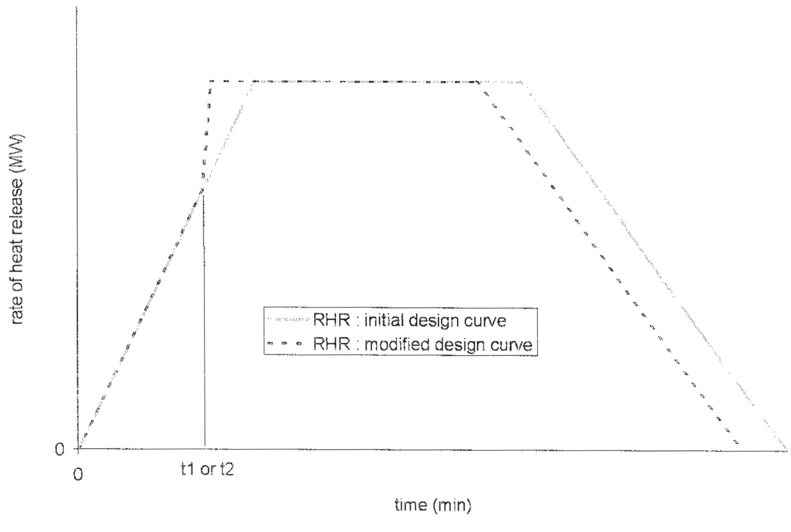


FIGURE 6.12: design curves for rate of heat release of the fire

The above approach is presented in the scheme of Fig. 6.13. In this scheme it is shown under which conditions (two- or one-zone modelling) the design temperature curves have to be determined.

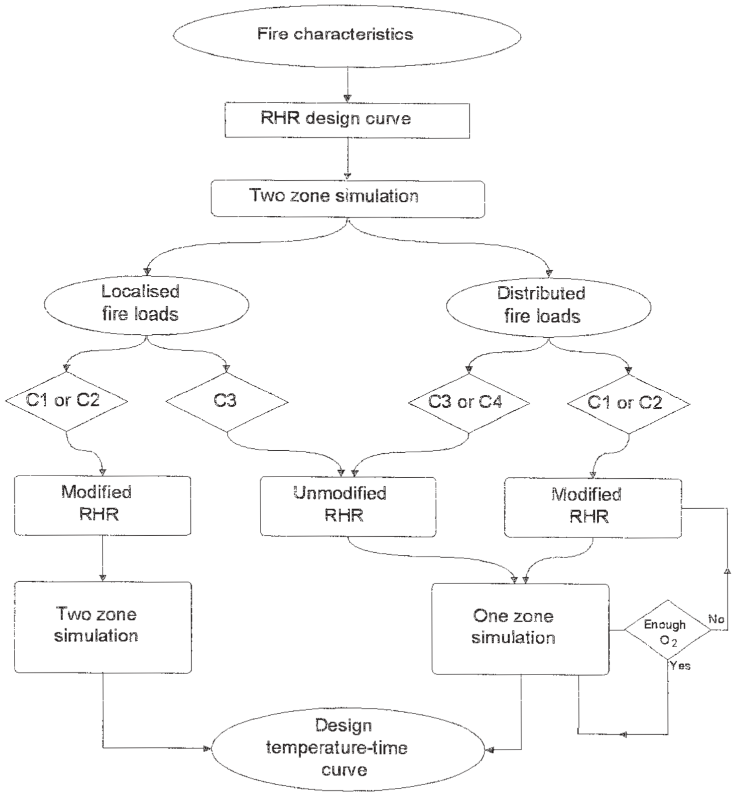


FIGURE 6.13

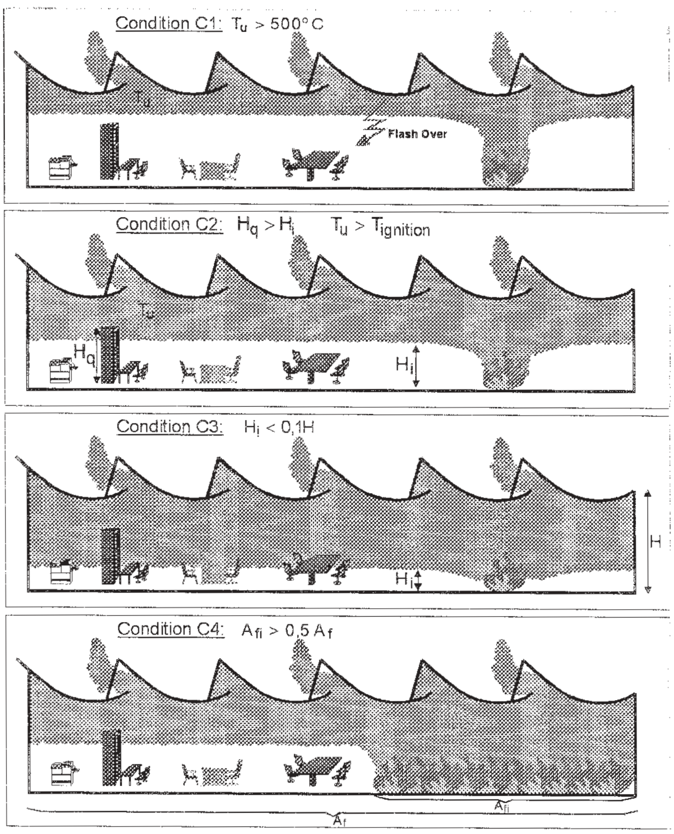


FIGURE 6.14

7 HEAT TRANSFER MODELS

In the last chapter we have seen the various models available to calculate the temperature inside a compartment as a function of time. To know the temperature of the structural elements as a function of time, it is necessary to calculate the heat flux to these elements.

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.

7.1 HEAT FLUX

At a given time (t), during the fire, the net heat flux to a surface is determined by considering thermal radiation and convection from and to the fire environment:

$$\dot{h}_{net} = \dot{h}_{net,c} + \dot{h}_{net,r} \qquad (7.1)$$

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

$$\dot{h}_{net,c} = \alpha_c \cdot (\theta_g - \theta_m) \qquad (7.2)$$

where:

α_c is the convection coefficient [W/m²/K]
θ_g is the gas temperature [°C]
θ_m is the structural element temperature [°C]

The radiative heat transfer is given by:

$$\dot{h}_{net,r} = \Phi\, \varepsilon_f\, \varepsilon_s\, \sigma \left[(\theta_g + 273)^4 - (\theta_m + 273)^4\right] \qquad (7.3)$$

where:

ε_f is the emissivity of the fire compartment (gas+boundaries)
ε_s is the emissivity of the structural element
θ_g is the gas temperature [°C]
θ_m is the structural element temperature [°C]
σ is the Boltzmann constant $5{,}67 \cdot 10^{-8}$ [W/(m².K⁴)]
Φ is the configuration factor

In standard ISO fire testing (furnaces) the resultant emissivity of the furnaces (gas+walls) is about 0,8. The emissivity for unprotected steel is 0,625, for concrete or fire protection materials a value of 0,7 can be used.

Regarding the convection coefficient in the furnaces values are found varying from 25 to 50 ($W/m^2/K$, standard vs. hydrocarbon fire).

In a real fire, the convection and emissivity coefficients of the compartment have to be changed as the optical properties of gases and gas velocity are not the same as in a furnace.

Concerning the convection heat transfers, the speed distribution provided by the pressure and density differences can be strongly non-uniform. It is then very complex to evaluate one global convective transfer coefficient. Nevertheless, some experimental studies point out that in case of furniture fire the maximum convective transfer coefficients are about 35 W/m^2 K.

The optical properties of combustion gases (radiation) are higher during the development of a real fire than in the furnaces. It is on the safe side to consider that the emissivity of the surrounding structural element is equal to 1. The emissivity of steel used in the furnaces will be kept and equal to 0,625.

The configuration factor Φ allows to take into account that some parts of the structural element can be eventually shielded from the radiation. By definition, the value of the configuration factor is taken between 0 and 1. The real value depends of the distance between the emitting and receiving surfaces, the size of surfaces and their relative orientation.

Where no specific data are available, the configuration factor can be conservatively taken as $\Phi = 1$.

When rough methods are used to calculate the mechanical behaviour of structural elements (such 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.

7.2 STEEL TEMPERATURE DEVELOPMENT

The calculation of the development of temperature fields in the cross section of a structural member exposed to fire involves solving Fourier's differential equation:

$$\frac{\partial}{\partial x}\left(\lambda_\theta \frac{\partial \theta}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda_\theta \frac{\partial \theta}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda_\theta \frac{\partial \theta}{\partial z}\right)+Q=\rho\, c_\theta \frac{\partial \theta}{\partial t} \tag{7.4}$$

where Q is the internal heat source that is equal to 0 in case of non-combustible walls. The boundary condition is expressed in term of the net heat flux $\dot{h}_{net,d}$.

Simple models for the steel temperature development calculation are based on the resolution of the equation (7.1) in the hypothesis of uniform temperature distribution in the cross section of the structural member.

Outside of these assumptions, advanced calculation methods can be used for the determination of the distribution of the temperature within structural members. In this case the thermal response model has to be based on:

- the realistic thermal action due to the fire;
- the variation of the thermal properties of the material for the relevant temperature range.

7.2.1 SIMPLE RULES FOR UNPROTECTED STEELWORK

For an equivalent uniform temperature distribution in the cross-section, the increase of temperature $\Delta\theta_{a,t}$ in an unprotected steel member during a time interval Δt may be determined from:

$$\Delta\theta_{a,t}=\frac{A_m/V}{c_a\,\rho_a}\,\dot{h}_{net,d}\,\Delta t \tag{7.5}$$

where:

A_m/V	is the section factor for unprotected steel members [m^{-1}];
A_m	is the exposed surface area of the member per unit length [m^2/m];
V	is the volume of the member per unit length [m^3/m];
c_a	is the specific heat of steel [J/kgK];
$\dot{h}_{net,d}$	is the design value of the net heat flux per unit area [W/m^2];
Δt	is the time interval [seconds], taken as not more than 5 seconds;
ρ_a	is the unit mass of steel [kg/m^3]

Some expressions for calculating design values of the section factor A_m/V for unprotected steel members are given in Table 7.1.

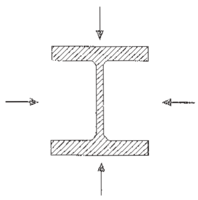
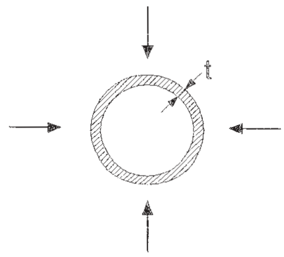
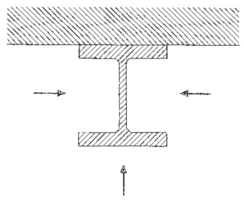
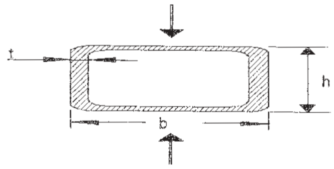
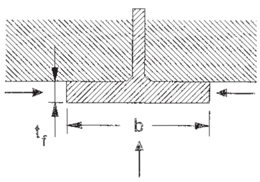
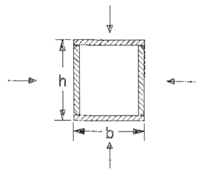
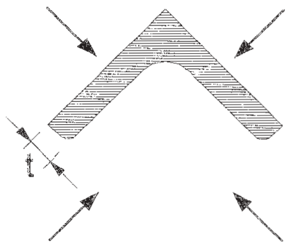
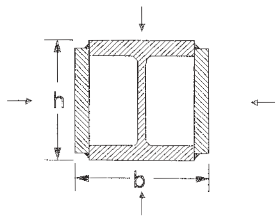
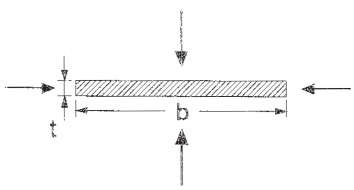
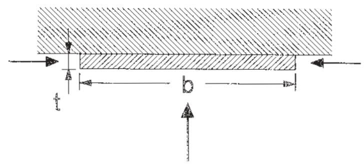
Open section exposed to fire on all sides: $\frac{A_m}{V} = \frac{perimeter}{cross\text{-}section\ area}$ 	*Tube exposed to fire on all sides:* $A_m / V = 1 / t$ 
Open section exposed to fire on three sides: $\frac{A_m}{V} = \frac{surface\ exposed\ to\ fire}{cross\text{-}\ section\ area}$ 	*Hollow section (or welded box section of uniform thickness) exposed to fire on all sides:* *If* $t \ll b$: $A_m / V \cong 1 / t$ 
I-section flange exposed to fire on three sides: $A_m / V = (b + 2t_f) / (bt_f)$ *If* $t \ll b$: $A_m / V \cong 1 / t_f$ 	*Welded box section exposed to fire on all sides:* $\frac{A_m}{V} = \frac{2(b + h)}{cross\text{-}section\ area}$ 
Angle (or any open section of uniform thickness) exposed to fire on all sides: $A_m / V = 2 / t$ 	*I-section with box reinforcement, exposed to fire on all sides* $\frac{A_m}{V} = \frac{2(b + h)}{cross\text{-}\ section\ area}$ 
Flat bar exposed to fire on all sides: $A_m / V = 2(b + t) / (bt)$ *If* $t \ll b$: $A_m / V \cong 2 / t$ 	*Flat bar exposed to fire on three sides:* $A_m / V = (b + 2t) / (bt)$ *If* $t \ll b$: $A_m / V \cong 1 / t$ 

TABLE 7.1: section factor A_m/V for unprotected steel members

7.2.2 SIMPLE RULES FOR STEELWORK INSULATED BY A FIRE PROTECTION MATERIAL

For a uniform temperature distribution in a cross-section, the temperature increase $\Delta\theta_{a,t}$ of an insulated steel member during a time interval Δt may be determined from:

$$\Delta\theta_{a,t} = \frac{\lambda_p A_p / V(\theta_{g,t} - \theta_{a,t})}{d_p c_a \rho_a (1+\phi/3)} \Delta t - \left(e^{\phi/10} - 1\right)\Delta\theta_{g,t} \tag{7.6}$$

but $\Delta\theta_{a,t} \geq 0$ if $\theta_{a,t} < \theta_{g,t}$

with:

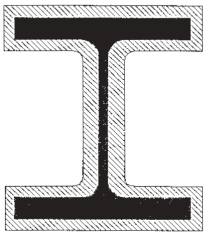
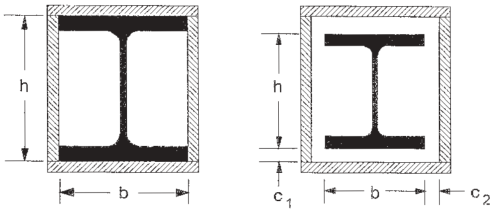
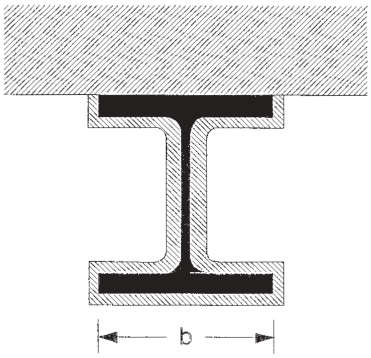
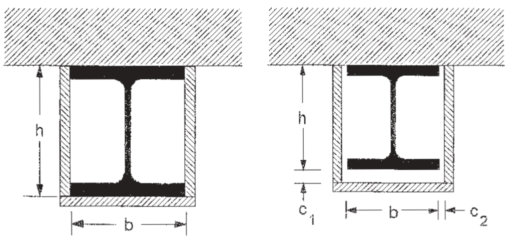
$$\phi = \frac{c_p \rho_p}{c_a \rho_a} d_p A_p / V \tag{7.7}$$

where:

A_p / V	is the section factor for steel members insulated by fire protection material [m^{-1}];
A_p	is the appropriate area of fire protection material per unit length of the member [m^2/m];
V	is the volume of the member per unit length [m^3/m];;
c_a	is the specific heat of steel [J/kgK];
c_p	is the specific heat of the fire protection material [J/kgK];
d_p	is the thickness of the fire protection material [m];
Δt	is the time interval [seconds], taken as not more than 30 seconds;
$\theta_{a,t}$	is the steel temperature at time t [°C];
$\theta_{g,t}$	is the increase of the ambient gas temperature during the time interval Δt [°C];
λ_p	is the thermal conductivity of the fire protection material [W/mK]
ρ_a	is the unit mass of steel [kg/m^3]
ρ_p	is the unit mass of the fire protection material [kg/m^3]

The area A_p of the fire protection material should generally be taken as the area of its inner surface, but for hollow encasement with a clearance around the steel member the same value as for hollow encasement without a clearance may be adopted.

Some design values of the section factors A_p/V for insulated steel members are given in Table 7.2.

Sketch	Description	Section factor (A_p/V)
	*Contour encasement of uniform thickness*	$\frac{\text{steel perimeter}}{\text{steel cross-section area}}$
	*Hollow encasement*[1] *of uniform thickness*	$\frac{2(b+h)}{\text{steel cross-section area}}$
	*Contour encasement of uniform thickness, exposed to fire on three sides*	$\frac{\text{steel perimeter} - b}{\text{steel cross-section area}}$
	*Hollow encasement*[1] *of uniform thickness, exposed to fire on three sides*	$\frac{2h+b}{\text{steel cross-section area}}$

[1] *The clearance dimensions c_1 and c_2 should not normally exceed $h/4$.*

TABLE 7.2: section factor A_p/V for steel members insulated by fire protection material

7.3 STRUCTURAL MODELS

Within structural models, there is a need to differentiate the schematisation of the structure to be checked and calculation models used for assessing the mechanical resistance of this schematised structure.

7.3.1 SCHEMATISATION OF THE STRUCTURE

The fire analysis of structures can be performed:

- either as a global structural analysis dealing with the entire structure, which should take into account the relevant failure mode in fire exposure, the temperature-dependent material properties and stiffness and the effects of thermal expansion and deformations;
- or as an analysis of parts of the structure. In this case, appropriate subassemblies should be selected on the basis of the potential thermal expansions and deformations, such that their interaction with other parts of the structure can be approximated by time-independent support and boundary conditions during fire exposure. The design effects of actions at supports and boundaries of subassemblies applicable at time $t = 0$, $E_{fi,d,t} = 0$, are assumed to remain unchanged throughout the fire exposure.
- or as a member analysis. In this case also the support and restraint conditions of the member, applicable at time $t = 0$, may generally be assumed to remain unchanged throughout the fire exposure. The buckling length ℓ_{fi} of any compression member for the fire design situation should generally be determined as for normal temperature design. However, for continuous columns in braced frames, the buckling length ℓ_{fi} may be reduced. In the case of a steel frame in which each level can be considered as a fire compartment with sufficient fire resistance, in an intermediate storey the buckling length of a continuous column ℓ_{fi} is equal to $0{,}5L$ whereas in the top storey the buckling length ℓ_{fi} is equal to $0{,}7L$, where L is the system length in the relevant storey.

As mentioned in Eurocodes, member analysis is mainly used when verifying nominal fire resistance requirements. When dealing with "real" fire developments, since the purpose is to have realistic evaluation of the fire behaviour of a "real" building, it is generally necessary to consider the interaction between members. This is due to the fact that it is difficult to know, a priori, if this interaction should be beneficial or not to the global structural behaviour, mainly when thermal gradients within members have to be considered.

7.3.2 CALCULATION METHODS

The load-bearing function of a structure, a part of it or a member shall be assumed to be maintained after a time t in a given fire exposure if

$E_{fi,d,t} \leq R_{fi,d,t}$

where:

$E_{fi,d,t}$ design effect of actions for the fire design situation, according to Eurocode 1 part 2.2

$R_{fi,d,t}$ corresponding design resistance of the structure or a part of it, for the fire design situation, at time t

To perform the analysis Eurocode 3 and 4, parts 1.2, are giving various levels of assessment methods that have not the same significance. Simple calculation models are restricted to member analysis whereas advanced calculation models are able to deal with any kind of schematisation of the structure.

7.3.2.1 Simple calculation models

For pure steel members (tensile members, columns, beams) the Eurocode 3- part 1.2 gives simple calculation methods for determining the load bearing resistance, for a temperature distribution obtained after a given duration of fire exposure, of:

- tension member with uniform or non-uniform temperature distribution across the cross-section:
- Compression members with uniform temperature distribution,
- beams with uniform or non-uniform temperature distribution, taking into account the risk of lateral-torsional buckling,
- members subjected to bending and axial compression, with uniform temperature distribution.

By using uniform temperature distribution, the verification of the load-bearing function may be carried out in the temperature domain. In this case, knowing the degree of utilisation μ_0 of a member, just at the starting of the fire, by:

$\mu_0 = E_{fi,d} / R_{fi,d,0}$

The critical steel temperature may be determined by:

$$\theta_{a,cr} = 39{,}19 \, . \ln \left[\frac{1}{0{,}9674 . \mu_0^{3{,}833}} \right] + 482$$

For composite members, some simple calculation methods given in the Eurocode 4-part 1.2 can be used. They are dealing with:

- composite slabs, for which the load-bearing resistance of simply supported or continuous slabs is obtained by applying the theory of plasticity, taking into account the temperature of reinforcement bars and of the concrete obtained according to equation 7.4. If a protection system is used to slow down the heating of the slab, it is assumed that the load-bearing criterion (R) is fulfilled as long as the temperature of the steel sheet is lower or equal to 350°C.
- composite beams, for which the load-bearing capacity is determined by considering a critical temperature or by calculating a bending moment resistance model based on simple plastic theory. The shear failure of stud connectors can also be taken into consideration.

Unfortunately for concrete filled hollow columns and for composite beams or columns comprising steel beams with partial or full concrete encasement, the simple calculation methods given in Eurocode 4 were developed only for the standard fire situation and cannot be easily transferred to other temperature-time curves. Consequently these kinds of composite elements need to be addressed by using advanced calculation methods.

7.3.2.2 Advanced calculation models

As mentioned in Eurocode 3 and 4, parts 1.2, advanced calculation models are based on fundamental physical principles to lead to a reliable approximation of the expected behaviour of the structure under fire conditions. They may be used in association with any temperature-time heating curve, provided that the material properties are known for the relevant temperature range.

Regarding the mechanical models, they have to be based on the acknowledged principles and assumptions of the theory of structural mechanics, taking into account the effects of temperature. Where relevant, the models shall also take account of:

- the combined effects of mechanical actions, geometrical imperfections and thermal actions,
- the temperature dependent mechanical properties of materials,
- geometrical non-linear effects,
- the effects of non-linear material properties, including the effects of loading and unloading on the structural stiffness.

Advanced calculation models may be used for individual members, for subassemblies or for entire structures, and are able to deal with any type of cross section.

Any potential failure modes not covered by an advanced calculation method (for instance, local buckling and failure in shear) shall be eliminated, in the design of the structure by appropriate means or detailing.

In general the advanced numerical models require a division of the structural element(s) under consideration into small elements. The size of the elements shall be chosen such that further refining will not significantly influence the general results. In general mesh refinement will lead to more accurate results. It is known however advanced numerical models based upon the finite element method suffer from so-called mesh-dependence, i.e. the results may be influenced significantly by size and orientation of the (finite) elements. This problem arises in cases were local phenomena like plastic hinges and concrete cracking occur. These local phenomena are generally “smeared” over the length of a finite element. Although overall structural behaviour may be simulated in good agreement with test results, locally predicted strains / stresses may become unrealistic. This problem is especially relevant in cases where rotation capacity governs the ultimate load bearing capacity such as the large rotations occurring at internal supports of continuous span slabs and beams.

Advanced models will, in general, be based on a so-called incremental iterative solution procedure. It shall be verified that time and/or load increments are chosen such that in each increment a properly converged solution is obtained.

8 CONCLUSION

This research has established a new concept called the **N**atural **F**ire **S**afety **C**oncept (NFSC concept) to analyse structural safety in case of fire. This NFSC procedure is more realistic and more economic 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 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 the budget dedicated to fire safety is used in a more efficient way.

The safety of the people has to be guaranteed. The objective may require a limit to the size of the compartment or the addition of 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 involves defining 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 dependent on the characteristic fire load. For these parameters, design tables and design guidance are given in Chapter 5 and in the WG3 report.

Occupancy / Activity	Fire Growth Rate	RHR_f [kW/m²]	Fire Load $q_{f,k}$ 80% fractile [MJ/m²]
Dwelling	Medium	250	948
Hospital (room)	Medium	250	280
Hotel (room)	Medium	250	377
Library	Fast	500	1.824
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 corresponding to different occupancies all related to γ_{q2} equal to 1

2. Then the design fire load $q_{f,d}$ 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 account of the fire compartment area
   - γ_{q2}, taking account of the fire activation risk
   - γ_{ni}, taking account of the different active fire fighting measures i (sprinkler, fire brigade, detection, automatic alarm transmission...). These active measures are generally imposed for life safety reasons.
   (see the 3 tables on page 75)

   Notes:
   - Factors γ_{q2}, γ_{n1} to γ_{n7} are given on page 75 for a fire compartment A_{fi} of 1.000 m². This is acceptable for design as on the safe side in most situations. If more precision is needed, please refer to tables 5.12, 5.14 and 5.15. In the last case, γ_{n7} should be taken as 1,0 if fire brigade intervention starts later than 30 minutes after alarm.
   - In case of high precision and combination of active measures, even table 5.13 could be activated.

   This design fire load is then used to determine the design Rate of Heat Release.
3. The design natural fire curve is then calculated 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 the 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.
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 failure. The fire resistance time $t_{fi,d}^{nat}$ may often be infinite such that the structure is able to support the loads from the beginning to the end of the fire.

This NFSC approach which consists of calculating the structural behaviour subjected to a natural fire curve taking into account the active fire fighting measures enables the designer to consider a more realistic action and therefore to optimise the safety. Moreover this natural fire safety concept enables the designer to make the trade-off between active and passive fire protection in a scientific and practical way. This safety quantification is based on the procedure already used by structural engineers for normal design at room temperature. The method has been extended to 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										
	Automatic Fire Suppression		Automatic Fire Detection			Manual Fire Suppression					$\gamma_n^{min} = \gamma_{n1} \cdot \ldots \cdot \gamma_{n10}$
	Automatic Water Extinguishing System	Independent Water Supplies (0 | 1 | 2)	Automatic fire Detection & Alarm by Heat	Automatic fire Detection & Alarm by Smoke	Automatic Alarm Transmission to Fire Brigade	Work Fire Brigade	Off Site Fire Brigade	Safe Access Routes	Fire Fighting Devices	Smoke Exhaust System	$\gamma_n^{max} = \gamma_{n4} \cdot \gamma_{n7}$
Title	γ_{n1}	γ_{n2}	γ_{n3}	γ_{n4}	γ_{n5}	γ_{n6}	γ_{n7}	γ_{n8}	γ_{n9}	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.

9 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 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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European Commission

EUR 20349 — Steel structures
Valorisation project — Natural fire safety concept

J.-B. Sleich, L.-G. Cajot, M. Pierre, D. Joyeux, G. Aurtenetxe, J. Unanua, S. Pustorino, F.-J. Heise, R. Salomon, L. Twilt, J. Van Oerle

Luxembourg: Office for Official Publications of the European Communities

2002 — 99 pp. — 21 x 29.7 cm

Technical steel research series

ISBN 92-894-3698-0

Price (excluding VAT) in Luxembourg: EUR 14.50