VTT RESEARCH NOTES 2497

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Survivability for ships in case of fire

Final report of SURSHIP-FIRE project

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puh. vaihde 020 722 111, faksi 020 722 4374

VTT, Bergsmansvägen 3, PB 1000, 02044 VTT
tel. växel 020 722 111, fax 020 722 4374

VTT Technical Research Centre of Finland, Vuorimiehentie 3, P.O. Box 1000, FI-02044 VTT, Finland
phone internat. +358 20 722 111, fax +358 20 722 4374

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Keywords fire, fire safety, fire safety design, ships, shipbuilding, fire simulation, evacuation, evacuation simulation, risk analysis

Abstract

Survivability of ships in case of fire has been studied in the SURSHIP-FIRE research project as a part of the SURSHIP cooperation, a coordinated European research program on Maritime safety. The work was performed in four subprojects related to materials used in shipbuilding, fire hazards on board, ship structures, and evacuation in ship conditions.

Fire test data of products commonly used in shipbuilding were stored to a free-of-charge accessible database for the use of design engineers. Guidelines were defined for using fire test data in simulation and product development.

Procedures for quantitative fire risk analyses of cabins and cabin areas were defined, applicable also to other cases with different features and details. A methodology for defining design fires for various ship spaces was formulated and applied to shops on board as a practical example. The sophisticated simulation and risk analysis tools utilized in the work were the FDS5 fire simulation program with its evacuation module FDS+Evac, the Probabilistic Fire Simulator, and the method of time-dependent event trees.

The effects of engine room fires on car deck structures were analysed in detail since the situation was recognised critical for the structural integrity of the ship. Thermal and mechanical analyses of the structures with different dimensions and insulation extents were performed considering both the standard fire curve and the hydrocarbon curve.

A survey of specific features of ship evacuation was carried out. Since the use of staircases and the movement of evacuees between decks is an essential part of ship evacuation, a new staircase sub-model for the FDS+Evac program was created, verified and validated.

The results of the SURSHIP-FIRE project can influence on IMO rules for alternative fire safety design of ships. The contributions of SURSHIP-FIRE are guidelines for using fire test data as input of simulations, a methodology for estimation of design fires, practices for quantitative risk analyses, a summary of critical fire situations for structures, and suggested improvements of the IMO guidelines for evacuation analyses.

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Tiivistelmä

Laivojen selviytymiskykyä tulipalossa tutkittiin SURSHIP-FIRE-projektissa osana eurooppalaista meriturvallisuuden SURSHIP-tutkimusohjelmaa. Työn neljä osatehtävää liittyivät laivanrakennuksessa käytettäviin materiaaleihin, tulipaloriskeihin laivoilla, laivojen rakenteisiin ja poistumiseen laiva-olosuhteissa.

Laivanrakennuksessa yleisesti käytettyjen tuotteiden palokoetuloksia tallennettiin maksuttomaan tietokantaan suunnittelijoiden käytettäviksi. Palokoetulosten käytölle simuloinnissa ja tuotekehityksessä laadittiin ohjeistus.

Hyttien ja hyttialueiden kvantitatiiviseen riskianalyysiin kehitettiin menettelytapoja, jotka ovat sovellettavissa ominaispiirteiltään erilaisten tapausten tarkasteluun. Mitoituspalojen määrittelyyn laivan eri tiloissa luotiin metodologia, jota sovellettiin laivan myymälätiloihin.

Konehuonepalon vaikutuksia autokannen rakenteisiin tutkittiin termisin ja mekaanisin analyysein. Rakenteita eri mittasuhtein ja eristyslaajuuksin tarkasteltiin sekä standardi- että hiilivetypalokäyrän mukaisessa palorasituksessa.

Laivan poistumistilanteille ominaiset piirteet kartoitettiin. Koska portaikkojen käyttö ja ihmisten siirtyminen laivan kannelta toiselle ovat laivoilla keskeinen osa poistumista, FDS+Evac-poistumislaskentaohjelmaan luotiin uusi validoitu portaikkomalli.

SURSHIP-FIRE-projektin tulokset voivat vaikuttaa laivojen vaihtoehtoista paloturvallisuussuunnittelua koskeviin IMO-säädöksiin. Projektin tuloksena syntyi ohjeistus palokoetulosten käytölle simuloinneissa, metodologia mitoituspalojen määritykseen, menettelytapoja kvantitatiivisiin riskianalyyseihin, rakenteille kriittisten tulipalotilanteiden yhteenveto ja kehitysehdotuksia poistumisanalyyseja koskevaan IMO:n ohjeistukseen.

Preface

ERA-NET TRANSPORT (ENT) is a sustainable network of national transport research programmes in Europe. Within the ERA-NET TRANSPORT, Action Group ENT5: SURSHIP (Survivability for ships) is a coordinated European research program on Maritime safety. One of the research projects of the SURSHIP program has been the “Survivability for ships in case of fire” (SURSHIP-FIRE), carried out at VTT Technical Research Centre of Finland in 2007–2009.

This report describes the results and conclusions of the SURSHIP-FIRE research project. SURSHIP-FIRE consisted of four subprojects:

I – Materials
II – Hazards
III – Structures
IV – Evacuation.

The general goals and anticipated benefits of SURSHIP-FIRE were the following:

- fire safety solutions of ships based on novel knowledge and computation techniques
- expansion of new fire safety design concepts in shipbuilding
- wide use of computation (simulation and risk analysis) in rule-making
- improvement of competitiveness by the application of novel knowledge
- improvement of maritime safety (products and ships as a whole).

The work in the SURSHIP-FIRE project was governed and supervised by a steering group which consisted of the representatives of the project sponsors. The members of the steering group represented Tekes (the Finnish Funding Agency for Technology and Innovation), the Finnish Maritime Administration, Shipping Enterprise Finstaship, companies in maritime product industry, and VTT.

During the SURSHIP-FIRE project, active cooperation and communication between the SURSHIP-FIRE research group and other fire-related projects of the SURSHIP program was created and maintained in the form of several fire safety workshops. In addition, the progress of the SURSHIP-FIRE project was reported to the Action Group ENT5 in meetings and workshops.

Contents

Appendices

1. Introduction

Since 2004, a comprehensive and powerful network of national ministries and supporting organisations in the field of transport research has been building up ERA-NET TRANSPORT (ENT). The goal of ENT is to improve the outcome and quality of transport research in Europe by facilitating cooperation among publicly financed transport research programmes.

Within the ERA-NET TRANSPORT, Action Group ENT5: SURSHIP (Survivability for ships) is a coordinated European research program on Maritime safety. A key idea of SURHSIP is to create improved know-how of a more generic, holistic ship safety approach which will influence ship owners, shipbuilders, suppliers and national administrations as well as the work on the International Maritime Organization (IMO). SURSHIP has the following three strategic objectives:

1. development of a holistic maritime safety concept
2. strengthening of the competitiveness of the European maritime industry
3. improvement of sustainability and safety of ships and of marine environmental protection.

SURSHIP is a coordinated concept involving eight EU member states (Germany, Denmark, Finland, France, the Netherlands, Poland, Sweden and United Kingdom). The Action Group ENT5 develops the overall scientific concept of SURSHIP and recommends subprojects for national funding. Each participating country gives input to the joint efforts through nationally supported subprojects, each of which is in line with and considered part of the joint initiative.

The “Survivability for ships in case of fire” (SURSHIP-FIRE) research project was carried out by VTT Technical Research Centre of Finland in 2007–2009. SURSHIP-FIRE consisted of the following four subprojects, included in the SURSHIP entity:

SURSHIP-FIRE subproject	**Acronym and title in SURSHIP**
I – Materials	FIREDATA – Database on fire behaviour of different materials/products.
II – Hazards	PROFIS – Probability based concept for fire development and spread in large/complex spaces.
III – Structures	SUNFE – Tools to analyse critical situations for structures under natural fire exposure.
IV – Evacuation	FES – Egress to muster stations in case of fire – application of new generation evacuation calculation method for ships.

1. Introduction

The interactions of the SURSHIP-FIRE subprojects and the connection to coordinated SURSHIP activities are shown in Figure 1.

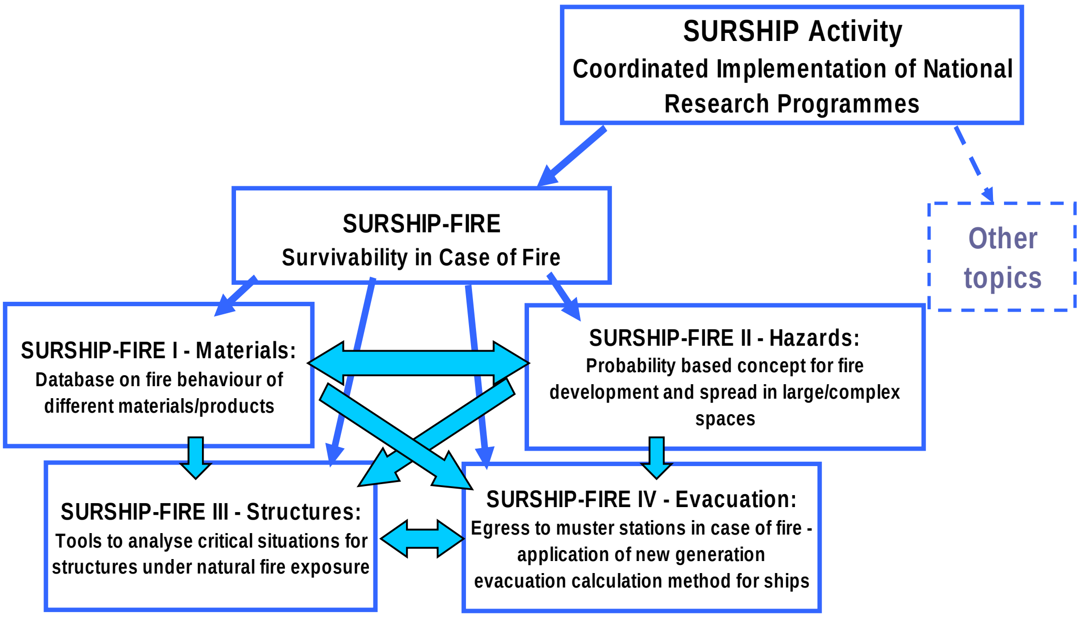

Figure 1. Interaction chart of the SURSHIP-FIRE project.

The fire safety requirements of ships have traditionally been based on fire tests of materials and structures, and criteria expressed as numerical values. In other words, only products passing the required fire tests [1] and meeting the criteria have been used in shipbuilding. However, the construction of large vessels and implementation of novel solutions based on class requirements and numerical criteria have been problematic.

Since 2001, it has been allowed to carry out fire safety design of ships also in alternative way [2]. The goal of alternative design and arrangements is to ensure an adequate level of fire safety of ships. The solutions to e implemented shall be proven sufficiently safe by means of fire safety engineering and risk analysis, and documented in detail. The adequate level of fire safety is demonstrated according to the Formal Safety Assessment document MSC 72/16 [3].

The general objective of the SURSHIP-FIRE project is to enhance the use and application of new knowledge and computation techniques in fire safety design of ships. The results of the project enable wide use of new fire safety concepts in design. The sophisticated simulation and risk analysis methodologies can also contribute to the development of IMO rules. The competitiveness of ship industry can be enhanced by the application of novel design methods. An essential goal is also the improvement of maritime safety by considering products and ships as a whole.

2. Subproject I – Materials

The main objective of Subproject I – Materials was to collect and combine available information on the key factors of fire performance of materials and products commonly used in shipbuilding. A set of data concerning heat release properties was analysed and arranged to a format useful for fire safety engineering. Data with permission to be publicly available was stored to a database and made available for design engineers free of charge in easy-to-use format. Description of the database is presented in 2.1. Practical meaning of the data in relation to fire performance levels of products need interpretations before they are useful in design and fire safety assessment. Thus, guidelines for using fire test data in simulations and product development were produced (see 2.2 and 2.3). Additionally, for materials contributing to cabin fires, several parameters need to be quantified for the use in simulations (see 2.4).

2.1 Fire performance database of materials and products for shipbuilding

The SP Fire Database [4] was chosen to be used for the shipbuilding products because this database already contains data which is useful in fire safety engineering analysis. Especially data from the cone calorimeter method ISO 5660 [5] can be utilised in fire safety assessment. To cover marine product data, the SP Fire Database was amended to include also IMO Fire Test Procedures Code (FTP Code) Part 5 (Surface flammability) [1, pp. 23–25 and 61–93] data. The database is free of charge for users, only registration is needed. Also new methods can be added to this database in the future.

To upload test data into the database essentially three items are needed: a vector data file, derived scalar data, and test information. Each item is described below.

Vector data

The vector data should be column-formatted in a text file, using semi-colon, comma or tab character as separator. The time column shall be in seconds and each column shall have a header including the unit (SI). The vector data file should contain only vector data plus headers and not other text or scalars.

Scalar data

The scalar data for the IMO FTP Code Part 5 method includes critical flux at extinguishment, CFE (kW/m^2), heat for sustained flaming, Q_{sb} (MJ/m^2), total heat release, Q_t (MJ) and peak heat release rate, Q_p (kW).

Test information

The test information is important since it defines what product is tested and how it is tested. It is the key to finding the right data for a user. This information is classified in several keywords according to Table 1 below. All text will be “searchable” for a user. Note that company names/owners of the results are reported only according to the acceptance of the owners.

Table 1. Keyword field descriptions and examples.

Keyword field	**Description**	**Examples**
Material 1 Material 2 Material 3 Material 4	Short description of the product tested including possible composition of different layers. Thickness (mm), area weight (g/m^2) and density (kg/m^3) can be given for each material/component.	Lacquer, type x Veneer Adhesive, type y Steel
Product	Product name. Thickness (mm), area weight (g/m^2) and density (kg/m^3) can be given for the whole product.	Veneer coated steel sheet
Method	Name of standardised fire test method.	IMO FTP Code Part 5, ISO 5660
Reference	Reference to the data source, i.e. a research project.	SURSHIP-FIRE, etc.
Comment	Test date and owner of the data.	Day. Month. Year Company Z
Import date	Date of uploading the data.	Day. Month. Year

Output of data

The data vector (such as heat release rate) can be presented as a function of time (see Figure 2 below).

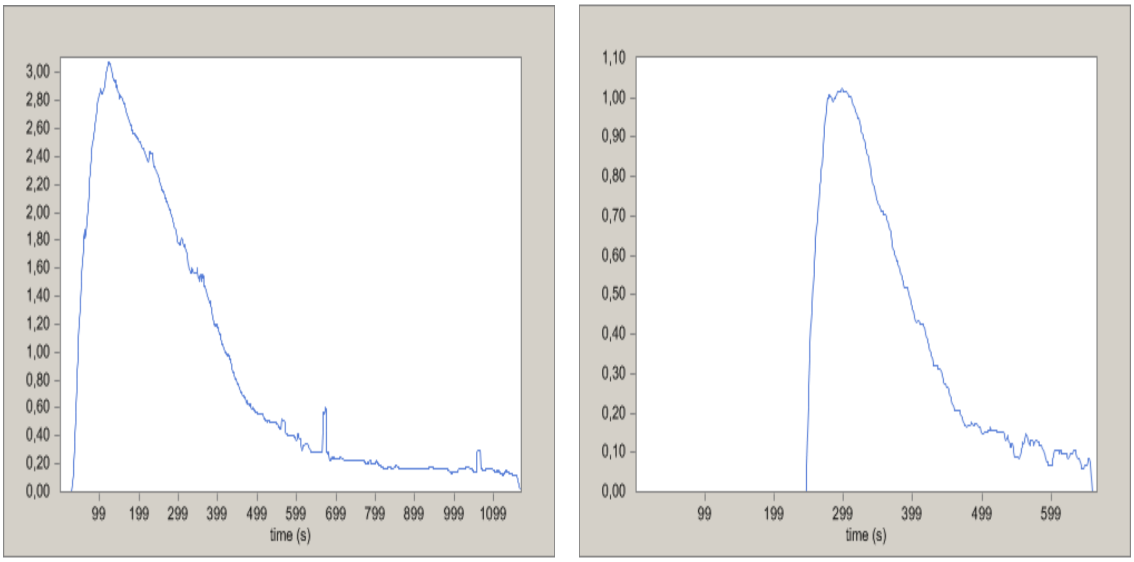

Figure 2. Examples of fire test data curves.

2.2 Use of IMO fire test data in simulation

Fire safety on board is regulated by SOLAS (Safety of life at sea) rules. The International Maritime Organization has specified a Fire Test Procedures Code (FTP Code) [1] to accompany the SOLAS rules. The FTP Code specifies e.g. the following test methods which are relevant for defining fire spread/heat release and smoke production properties of products:

- surface flammability of bulkhead, wall, and ceiling finish materials; primary deck coverings; plastic pipes; and electrical cables (Part 5 of Annex 1 to the FTP Code)
- smoke and toxicity of bulkhead, wall, and ceiling finish materials; plastic pipes; and electrical cables (Part 2 of Annex 1 to the FTP Code).

In addition to these methods, also the test method for calorific value (EN ISO 1716 [6]) is referred in the IMO rules.

Meaning and use of low flame spread (FTP Code Part 5) limits

A specimen of size 155 mm × 800 mm and of normal thickness 50 mm or less is inserted to the test apparatus in a vertical position so that its longer side is horizontal (see picture of the apparatus in Table 2). The specimen is exposed to a defined heat radiation. The highest intensity of heat radiation at the nearest end of the specimen is 50.5 kW/m² and it decreases from this value towards the other end according to a defined curve. The time to ignition, spread of flame, extinguishment of flame, and heat for sustained burning are measured during the test. Surface flammability criteria according to IMO FTP Code Part 5 are given in Table 2.

Table 2. Surface flammability criteria (low flame spread) [1].

Quantity	**Floor coverings**	**Bulkhead, wall and ceiling linings**	
CFE (kW/m^2)	≥ 7.0	≥ 20.0	
Q_{sb} (MJ/m^2)	≥ 0.25	≥ 1.5	
Q_t (MJ)	≤ 2.0	≤ 0.7	
Q_p (kW)	≤ 10.0	≤ 4.0	

CFE = critical flux at extinguishment
Q_{sb} = heat for sustained burning
Q_t = total heat release
Q_p = peak heat release rate
IMO FTP Code Part 2, Smoke and toxicity test not required if $Q_t \leq 0.2$ MJ and $Q_p \leq 1.0$ kW

The limits of the IMO FTP Code Part 5 criteria are interpreted in the following as key values from the cone calorimeter method ISO 5660 [5] which gives more useful input values for fire simulation. It is assumed that the cone calorimeter heat flux is 50 kW/m^2.

For <u>bulkhead, wall and ceiling linings</u> the maximum area which can burn in the IMO FTP Code Part 5 method is about 0.053 m^2. Taking into account the heat release (Q_p) limit 4 kW, the total heat release (Q_t) limit 0.7 MJ and the effect of different specimen orientations (heat release in horizontal orientation (ISO 5660) can be twice as high as in the vertical orientation (FTP Code Part 5)), the following 'worst case' values can be used as input values in simulation for products fulfilling low flame spread criteria:

- maximum for heat release rate 150 kW/m^2
- maximum for total heat release, THR 13 MJ/m^2 (burning time maximum 1.5 min)
- time to ignition at least about 20 s
- for the best performance products having $Q_t \leq 0.2$ MJ and $Q_p \leq 1.0$ kW the following limits can be applied: maximum RHR 40 kW/m^2, maximum THR 3.8 MJ/m^2.

For <u>floor coverings</u> the maximum area which can burn in the IMO FTP Code Part 5 method is about 0.074 m^2. The heat release ($Q_{p)}$ limit is 10 kW, the total heat release (Q_t) limit is 2.0 MJ and the specimen orientation effect is as described above for testing bulkhead, wall and ceiling linings. This leads to the following ‘worst case’ values to be used as input values in simulation for products fulfilling low flame spread criteria:

- maximum for heat release 250 kW/m^2
- maximum for total heat release THR 27 MJ/m^2 (burning time max 2 min).

Note that in all cases the heat of combustion of the product in the thickness used must be ≤ 45 MJ/m^2.

Meaning and use of smoke and toxicity (FTP Code Part 5) limits

Products having only very limited contribution to fire spread (i.e., products having $Q_t \leq 0.2$ MJ and $Q_p \leq 1.0$ kW and thus not required to be tested according to IMO FTP Code Part 2, Smoke and toxicity test) can be estimated to have the following behaviour:

- The mass/unit area of combustible material for these products is ≤ 100–200 g/m^2 depending on the heat of combustion of the material of concern (assumed to be 15–30 MJ/kg in the above given mass/unit area range).
- Total smoke production can be estimated using the above given masses per unit area of combustible material together with smoke yields (g/g burned substance) relevant for the materials of concern.
- Similarly, total production of gas species can be estimated using the above given masses per unit area of combustible material together with gas yields (g/g burned substance) relevant for the materials of concern.

For products having $Q_t > 0.2$ MJ and $Q_p > 1.0$ kW, the estimation of smoke and gas production will be more difficult, but if estimates for masses per unit area of combustible material are available, the above described principles can be applied also for these products. In practice, the highest limits for masses per unit area of combustible material can be in the range of 1–5 kg/m^2 for acceptable products.

Method for calorific value (EN ISO 1716)

Earlier it was noted that in all cases the heat of combustion per unit area of the product must be ≤ 45 MJ/m^2 in the thickness used. The method used in defining the heat of combustion is EN ISO 1716 [6]. In this method, 0.5 g of material is used to define the energy produced by a complete combustion of the substance.

2.3 Use of IMO fire test data in product development

For the use in product development, the limits of the IMO FTP Code Part 5 criteria are interpreted in the following as key values from the cone calorimeter method [5] to give useful values for estimating product performance. It is assumed that the cone calorimeter heat flux is 50 kW/m^2.

For bulkhead, wall and ceiling linings the maximum area which can burn in the IMO FTP Code Part 5 method is about 0.053 m^2 and taking into account the heat release (Q_p) limit 4 kW and the total heat release (Q_t) limit 0.7 MJ, the following values can be used as estimates for product fulfilling low flame spread criteria:

- maximum for heat release rate 80 kW/m^2
- maximum for total heat release, THR 13 MJ/m^2
- time to ignition at least about 40 s
- for the best performance products having $Q_t \leq 0.2$ MJ and $Q_p \leq 1.0$ kW the following limits can be applied: Maximum RHR 25 kW/m^2, maximum THR 3.8 MJ/m^2.

For floor coverings the maximum area which can burn in the IMO FTP Code Part 5 method is about 0.074 m^2, the heat release (Q_p) limit is 10 kW and the total heat release (Q_t) limit is 2.0 MJ. This leads to the following values to be used as estimates for products fulfilling low flame spread criteria:

- maximum for heat release rate 150 kW/m^2
- maximum for total heat release THR 27 MJ/m^2.

Note that in all cases the heat of combustion of the product in the thickness used must be ≤ 45 MJ/m^2.

2.4 Fire parameters for materials involved in cabin fires

In a cabin fire, inner surfaces of ceilings and walls, floor coverings, furniture (including mattresses and bedclothes), curtains and other decorations, luggage and clothes of passengers may contribute to the fire development. The fire load of these items can be defined based on the materials included. However, to be able to use material data in simulation of cabin fires e.g. the following parameters need to be quantified:

- thermal conductivity (W/Km)
- specific heat capacity (J/Kkg)
- emissivity of surfaces
- heat of reaction (J/kg)
- heat of combustion(J/kg).

Values for these parameters can be found from handbooks, e.g. The SFPE Handbook of Fire Protection Engineering [7].

Design fires depend on the fire load, fire performance of materials, room lay-out and ventilation conditions. Fire performance of products with large flat areas is reasonably easy to estimate based on handbook values, but ‘non-standard’ items such as clothes may be difficult to estimate without experimental tests (full scale or cone calorimeter + effective burning area estimates).

3. Subproject II – Hazards

In Subproject II – Hazards, quantitative risk analysis of ship fire safety was performed. Ship fire statistics and fire frequencies were reviewed. Risk analytic evaluations were applied to a cabin and a cabin area. A methodology for fire safety engineering design of various ship spaces was defined and applied to tax-free and specialty shops on board. As a result of this subproject, a concept for assessment of hazard probability of critical spaces of ships was created.

In this chapter, the basics of the Fire Safety Engineering design process and a methodology for defining design fires are described. Since statistics are an important source of information for assessing fire risks, a short literature review of ship fire statistics and fire frequencies is presented. Risk-based fire safety analyses of a cabin and a cabin area are reported. The methodology for defining design fires is applied to shops on board.

3.1 Basics of Fire Safety Engineering design process

In performance-based design, the assessed level of fire risk defines the acceptability of the design. It is therefore essential that all features affecting the total fire risk are included in the analysis. All factors must be quantified, such as ignition and fire development, performance of structural elements, behaviour and actions of people on board (the crew and passengers), level and reliability of fire safety systems (incorporating both active and passive measures), intervention by fire fighting, and damages caused by the fire.

Self-explanatory schemes shown in Figures 3 and 4 present the Fire Safety Engineering (FSE) design process and the basic factors of FSE analysis. The schemes are oriented on buildings, but the same factors and processes are applicable to ships as well.

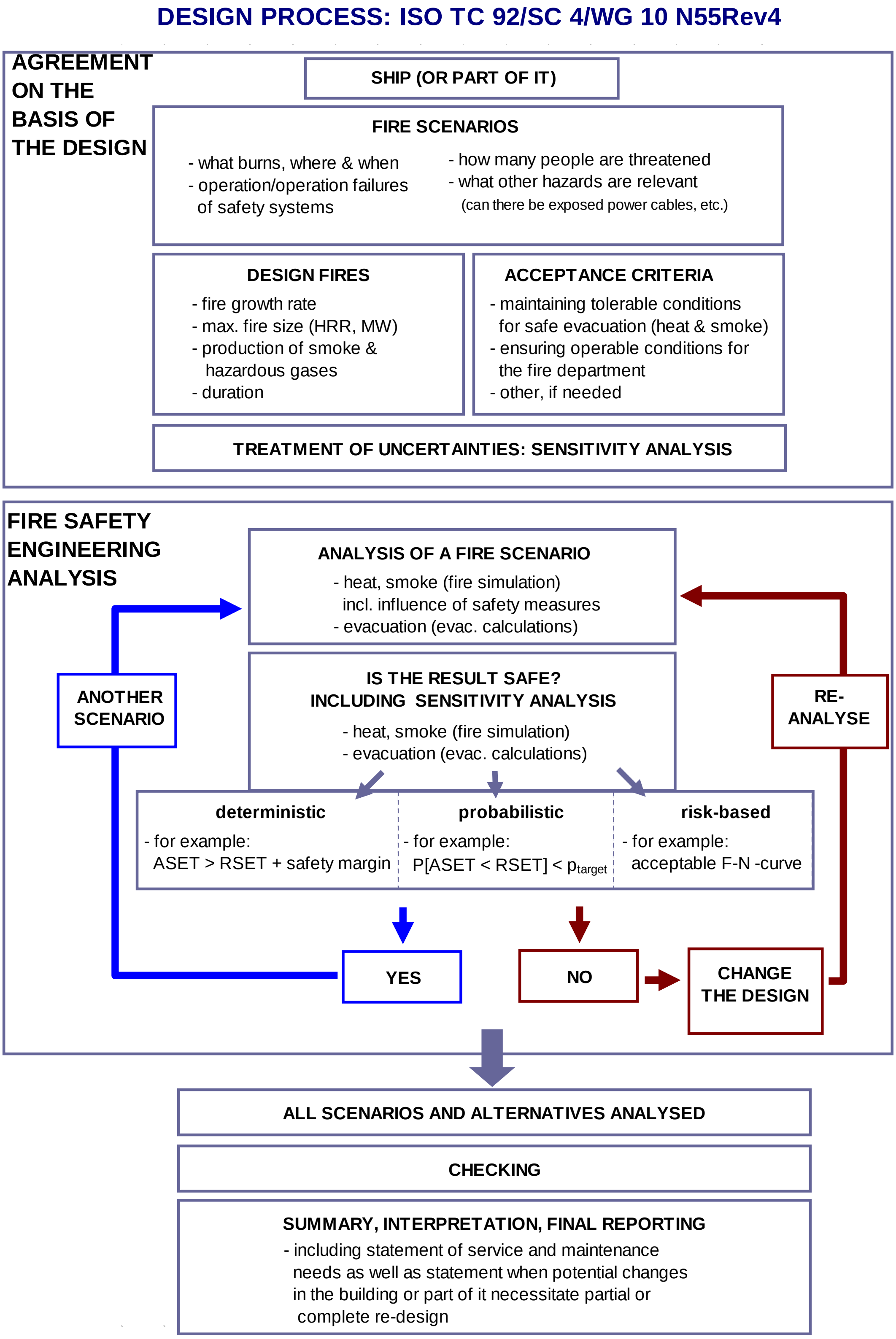

Figure 3. Fire safety engineering (FSE) design process scheme (ASET = available safe egress time; RSET = required safe egression time).

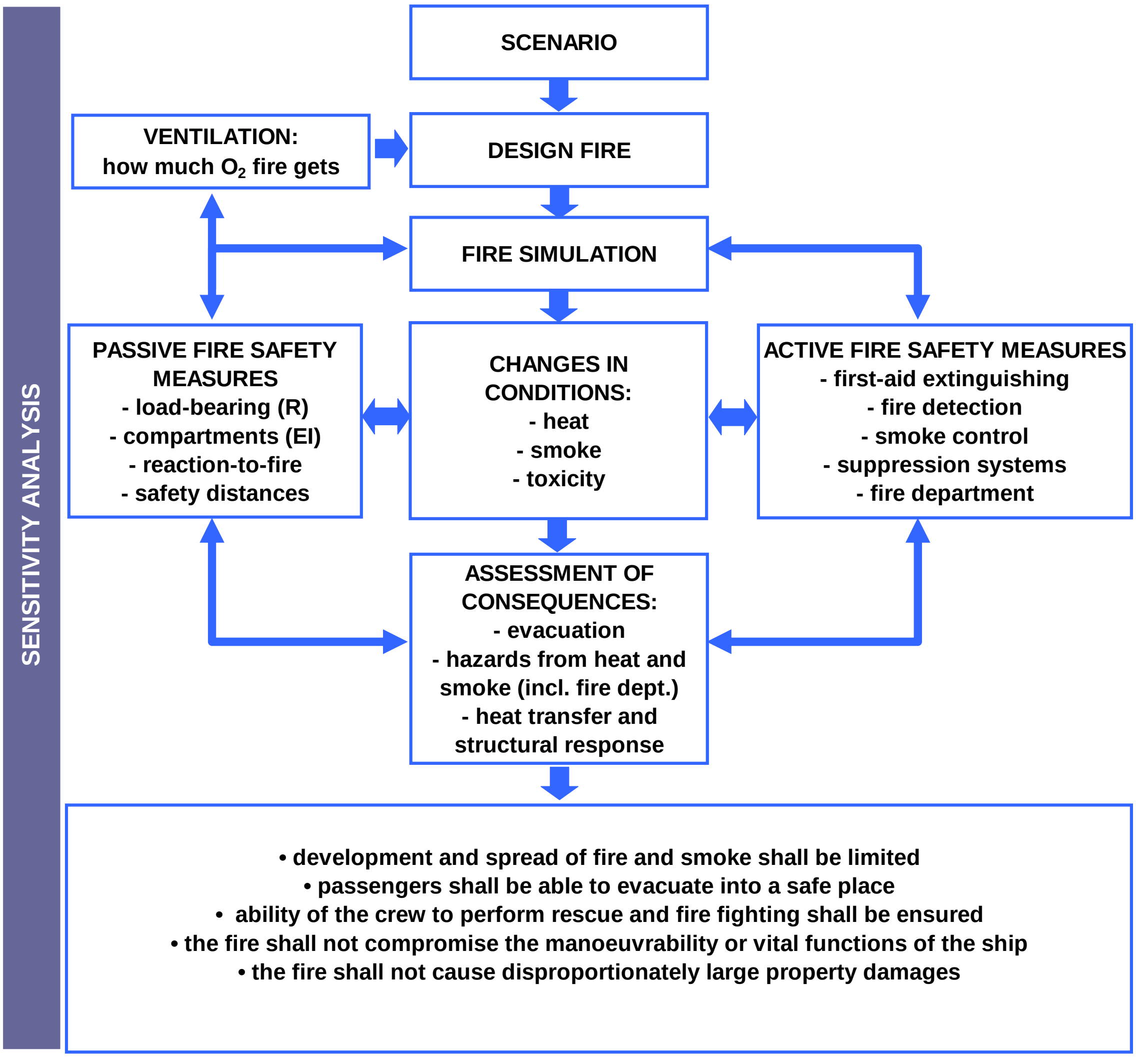

Figure 4. Fire safety engineering analysis scheme.

The most important quantity in describing a fire and its development is the heat release rate. Therefore, the main emphasis in this chapter is placed on heat release and fire spread. As a result of burning, however, also smoke and toxic gases are produced. These factors shall be taken into account in FSE design process and fire risk analyses because of their effects especially on people. The parameter in the analysis of smoke and toxic gas production is the yield (mass produced / mass burned). In the evaluation of smoke and various toxic gases, it must be also noticed that their yields are strongly dependent on the materials burning, as well as on the conditions of the fire; i.e. the temperature and the availability of oxygen.

3.2 Estimation of design fires

We apply an approach in which the combustibles are described as fire-load units. In this approach, the fire compartment analysed is filled with a suitable number of fuel-packages with proper dimensions and placing. For simplicity of presentation, the fire-load units are rectangles with all faces but the one directed to floor releasing heat according the specifications of the particular fire-load unit.

The development of the fire is described as follows:

- One fire load unit is selected by the user as the initial fire.
  - Typically, one has to use several initial fire positions even in a single analysis to achieve a sufficiently comprehensive picture of the fire incident.
- All other fire-load units are secondary igniting objects that will ignite when their surface temperature reaches the ignition temperature specified by the user. After ignition, the ignited fire-load unit starts to release heat following the same time evolution as the initial fire.
- It should be noted that ventilation is the most important factor influencing the fire development because fire cannot continue burning unless there is supply of fresh air and exhaust of the smoke gases. Typically, ventilation takes place via
  - voids and cracks in the ship envelope
  - normal HVAC systems
  - windows that break and fallout due to heat exposure generated by the fire
  - smoke exhaust systems.
- The influence of fire suppression is partially incorporated into the fuel-package descriptions and partially it must be assessed by the user as follows:
  - The influence of normal sprinkler system on the heat release rate (HRR) development is incorporated in the fuel-package description (see section 3.2.6). The influence of other automatic suppression systems such as water mist systems and gaseous suppression systems is not included in the fuel-package description and must be analysed separately by consulting proper regulations and experts.
  - The influence of fire fighting is not directly incorporated in the fuel-package description but must be taken into account through a post-processing procedure described in section 3.2.7.
  - The influence of first-aid extinguishing is not incorporated in the fuel-package description.

3.2.1 Determination of heat release rate curves of initial fire

There are basically two ways to assess the heat release rate (HRR) in fires:

1. analysis and synthesis of experimental data
2. modelling and fire simulation.

Whenever there is reliable and relevant data available, it should be used. There is abundantly of experimental data available but in general, the larger fires one has to consider, the less relevant data exists. In this case, HRR can be estimated using modelling and fire simulation. These two approaches are described below in more detail.

3.2.1.1 Obtaining HRR curves on the basis of analysis and synthesis of experimental data

The basic constituent of the fuel-package approach is a rectangular object that releases heat according to a certain time dependent function which is determined from fire experiments. The procedure of how the experimental data is processed is exemplified below for office fires:

1) First, all the data available in literature is compiled (an example of compilation of data relevant to office fires is shown in Figure 5) and given as a simplified model representation (an example of this simplification is shown in Figure 6). In the model used, the growth phase of the fire is modelled by a $\sim t^p$ dependence where the power p is usually 2; after the growth phase at time t_1 the fire burns at a steady HRR until time t_2 when it starts to decay; in most cases the decay phase is best modelled by using an exponential model in which HRR decreases as $\sim \exp(-(t-t_2)/\tau)$, where τ is the parameter characterizing how fast HRR decays.

2) Next, the compiled data is analysed to obtain parameters that allow generalisation of the results. For example, in the office workstation case, the data are obtained from workstations of different sizes. A suitable generalisation parameter is HRR per unit area of the workstation ($\text{HRR}''_{\text{max}}$). Similarly, the total heat released during the burning is the total energy released per unit area of the workstation (q'').

3) Next, all the characteristic fire parameters are tabulated (see Table 3) and analysed using statistical methods, see Figure 7.

4) Finally, suitably high or low fractiles[1] of the characteristic fire parameters are selected to describe the fire-load units.

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[1] High fractiles are used for $\text{HRR}''_{\text{max}}$, q'' and τ, and low fractile for t_g.

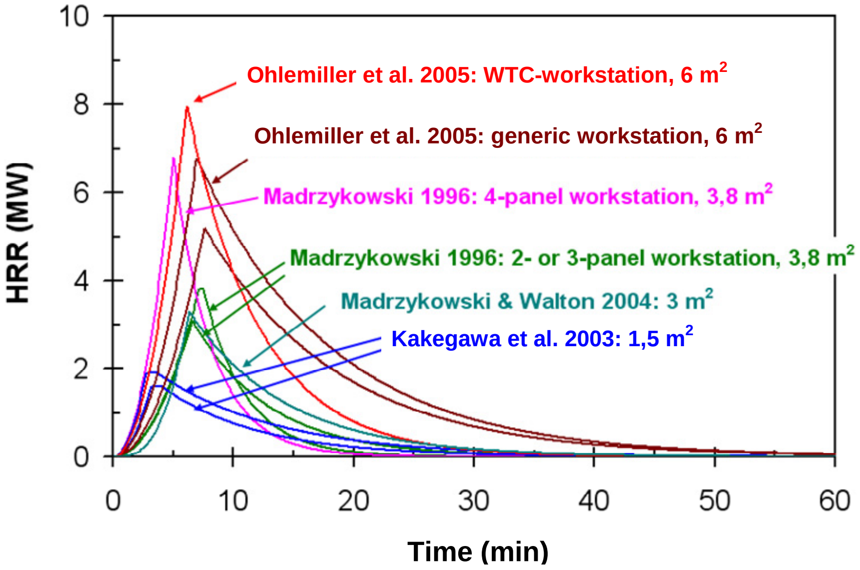


Figure 5. Data from fire experiments with office workstations [8, 9, 10, 11].

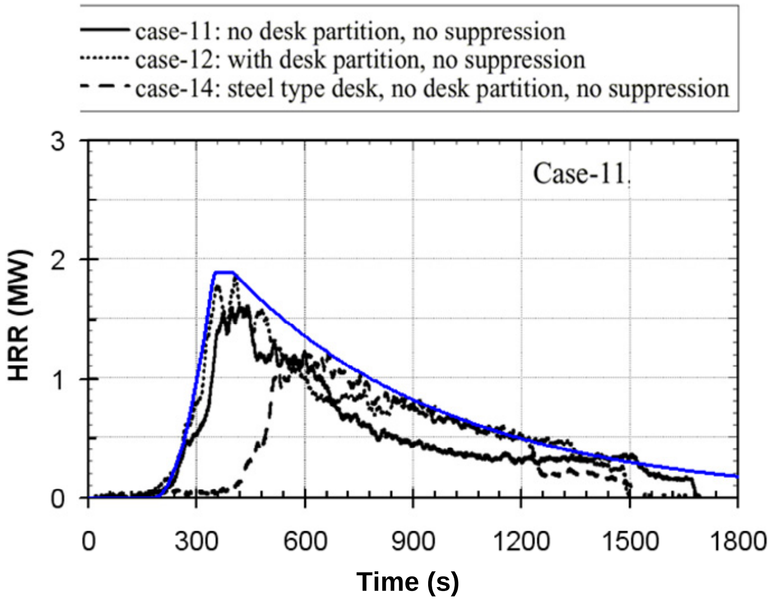


Figure 6. Example of modelling of experimental heat release rate (HRR) data by a simplified model.

Table 3. Parameters describing office workstation fires.

	Madrzykowski 1996 2-panel workstation	Madrzykowski 1996 3-panel workstation	Madrzykowski 1996 4-panel workstation	Kakegawa et al. 2003 case 11	Kakegawa et al. 2003 case 12	Ohlemiller et al. 2005 generic workstation, test 2	Ohlemiller et al. 2005 generic workstation, test 3	Ohlemiller et al. 2005 WTC-workstation, test 4	Madrzykowski & Walton 2004 County Cook workstation	average	standard deviation
p	2	2	2	2	2	2	2	2	3		
t_g (s)	225	220	115	150	120	160	200	130	255	175	51
HRR_{max} (kW)	3100	3800	6800	1600	1900	6800	5200	8000	3300		
t_1 (s)	396	429	300	190	165	417	456	368	380		
t_2 (s)	–	450	–	240	220	–	–	–	–		
τ (s)	380	210	190	480	600	660	660	360	480	447	177
Q_{tot} (MJ)	1587	1422	1972	958	1358	5444	4225	3907	1916		
D_{eff} (m)	2.19	2.19	2.19	1.38	1.38	2.75	2.75	2.75	1.97		
A_b (m)	3.78	3.78	3.78	1.50	1.50	5.95	5.95	5.95	3.04		
HRR''_{max} (kW/m^2)	820	1005	1799	1067	1267	1142	873	1344	1086	1156	294
q'' (MJ/m^2)	420	376	522	639	905	914	710	656	630	641	188

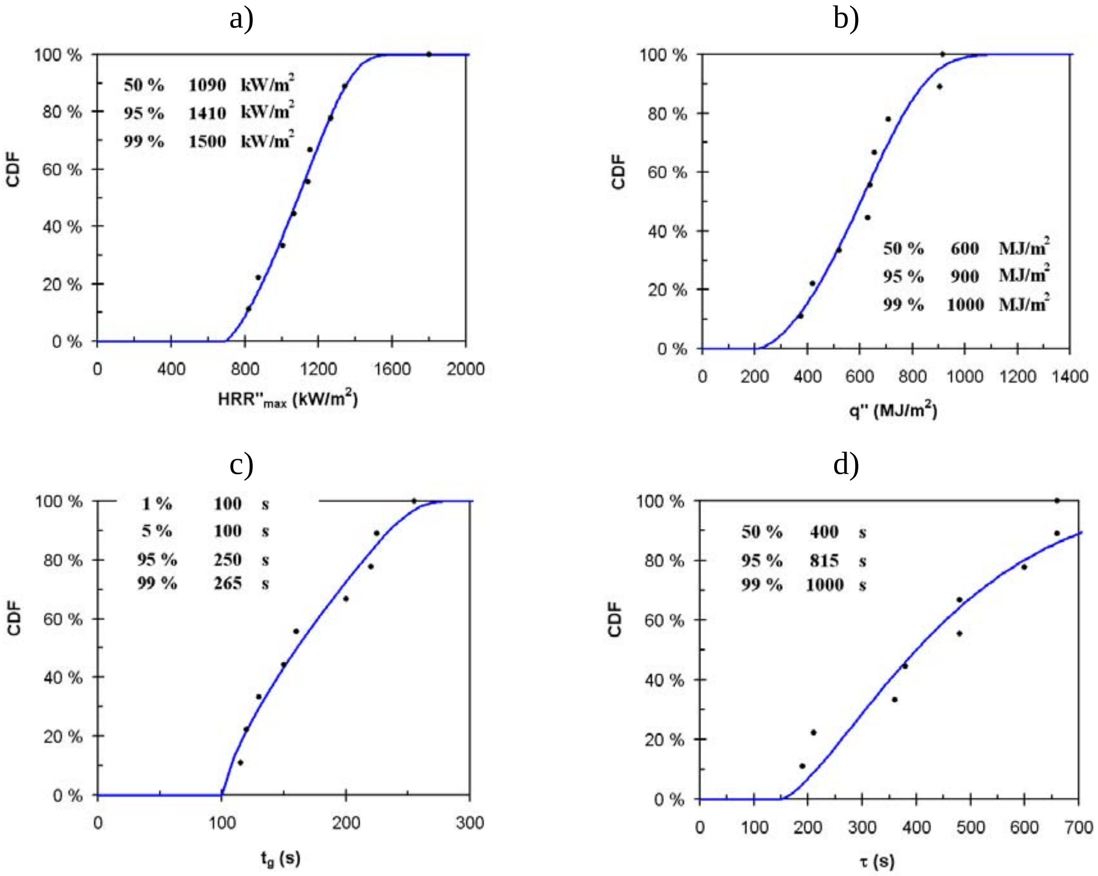


Figure 7. Example of statistical analysis of data of fire experiments of office workstations: a) HRR per unit area of the workstation, b) total heat release per unit area of the workstation, c) HRR growth time factor t_g and d) HRR decay factor τ (CDF = cumulative density function).

3.2.1.2 Estimating HRR curve on the basis of modelling and fire simulation

When relevant data is not available, it is possible to use modelling and fire simulation to assess the heat release rate. A novel methodology, enabled by the version 5 of the FDS fire simulation program, has been developed *for using the fire simulation program to predict the heat release rate*.

The methodology utilises basic combustion characteristics that are simply measurable, i.e.

- the Heat Release Rate Per Unit Area (HRRPUA [kW/m^2]) that can be measured by the cone calorimeter and hence, due to the simplicity of the measurement, data is already available for most combustibles in our living environment
- the Effective Heat of Combustion (EHC [MJ/kg]) that can be measured by the cone calorimeter or some other calorimetric technique such as the bomb calorimeter.

The other parameters that have to be specified are

- density ρ [kg/m^3]
- specific heat c [JK^{-1}kg^{-1}]
- thermal conductivity k [WK^{-1}m^{-1}]
- ignition temperature T_{ig} [°C]
- timing of the ignition and early HRR evolution: ignition time t_{ig} [s] and time-to-peak HRRPUA t_{p} [s]
- the amount of combustible material and its characteristic thickness [m]
- geometry: overall size (floor area and volume), voids and spatial extensions in the *xyz*-directions [m]
- the size of the initial fire (area and heat release rate) that describes the fire ignition, and its position.

The use of this methodology requires careful analysis and, naturally, the approach must be validated. The results show that – given the inherent uncertainties involved in our knowledge of the fire load of a particular building – the accuracy of HRR predictions obtained by using the methodology is sufficient for FSE usage. As a practical example, the application of the methodology on design fires for shops on board is presented in section 3.6.

3.2.2 Selection of the number of fire-load units

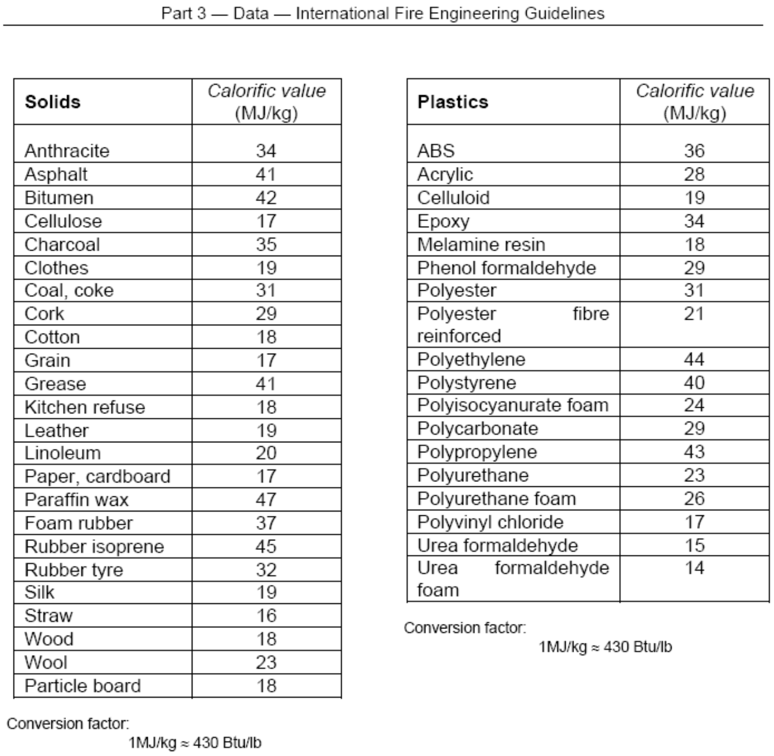
To assess the number of fire load units in a space, one must have an estimate on the energy Q_{unit} [MJ] that a fire load unit can release in the fire and the fire-load density q'' [MJ] that nowadays is expressed per floor area of the space considered.

The energy Q_{unit} that a fire load unit can release in the fire is a weight averaged product of the effective heat of combustion $\Delta H_{c,eff,k}$ and the mass M_k of the $k = 1, 2, \ldots, K$ combustibles in the fire load unit

$$Q_{unit} = \sum_{k=1}^{K} \varphi_k \cdot \Delta H_{c,eff,k} \cdot M_k \tag{3-1}$$

where the proportions sum up to unity $\sum_{k=1}^{K} \varphi_k = 1$. The effective heat of combustion $\Delta H_{c,eff,k}$ differs from the heat of combustion $\Delta H_{c,k}$ by a factor χ taking into account that in fires the combustion is rarely complete. Typical values suggested to the factor χ range around 80 %; a safe-side assumption is to set the factor $\chi = 1$. Heats of combustion of some typical fuels are listed in Table 4.

Table 4. Heat of combustion values of typical fuels [12].



Part 3 — Data — International Fire Engineering Guidelines

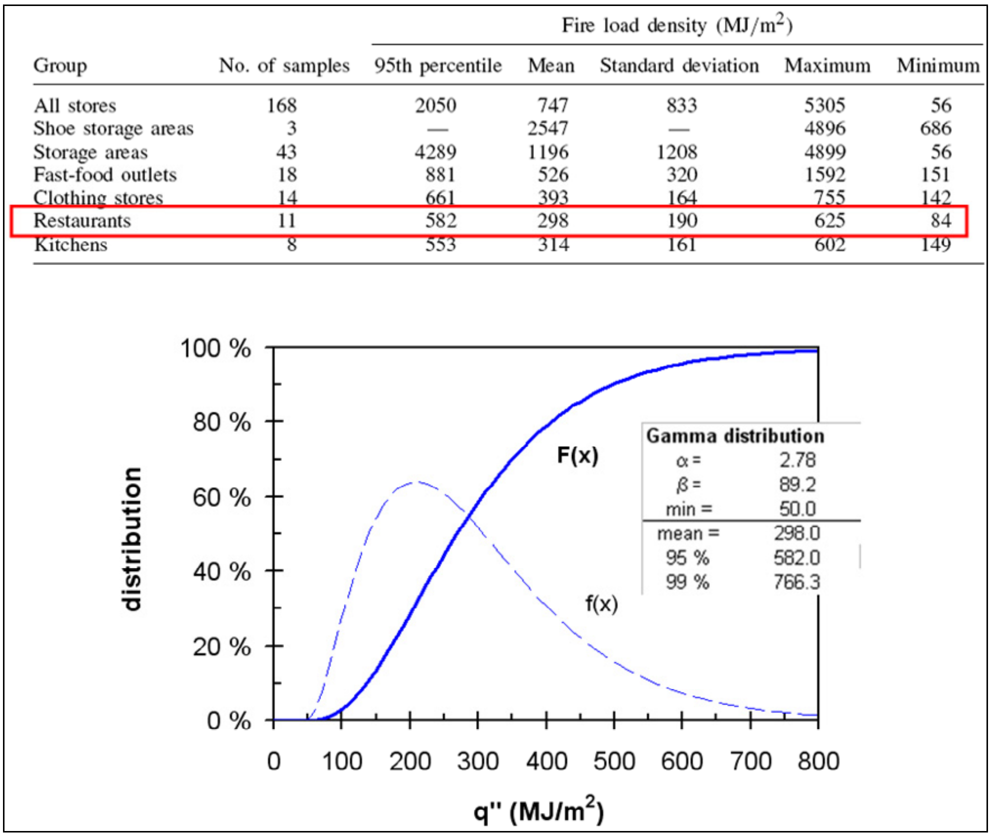
Solids	*Calorific value* (MJ/kg)
Anthracite	34
Asphalt	41
Bitumen	42
Cellulose	17
Charcoal	35
Clothes	19
Coal, coke	31
Cork	29
Cotton	18
Grain	17
Grease	41
Kitchen refuse	18
Leather	19
Linoleum	20
Paper, cardboard	17
Paraffin wax	47
Foam rubber	37
Rubber isoprene	45
Rubber tyre	32
Silk	19
Straw	16
Wood	18
Wool	23
Particle board	18

Conversion factor:
1MJ/kg ≈ 430 Btu/lb

Plastics	*Calorific value* (MJ/kg)
ABS	36
Acrylic	28
Celluloid	19
Epoxy	34
Melamine resin	18
Phenol formaldehyde	29
Polyester	31
Polyester fibre reinforced	21
Polyethylene	44
Polystyrene	40
Polyisocyanurate foam	24
Polycarbonate	29
Polypropylene	43
Polyurethane	23
Polyurethane foam	26
Polyvinyl chloride	17
Urea formaldehyde	15
Urea formaldehyde foam	14

Conversion factor:
1MJ/kg ≈ 430 Btu/lb

Data on fire load densities relevant to ships is scarce, but some guidance may be obtained from recent statistical analysis of ashore premises, such as papers by Thauvoye et al. [13] presenting, e.g., data relevant to hotels, and by Zalok et al. [14] presenting data relevant to restaurants and commercial premises (see Figure 8).



Group	No. of samples	Fire load density (MJ/m²) 95th percentile	Mean	Standard deviation	Maximum	Minimum
All stores	168	2050	747	833	5305	56
Shoe storage areas	3	—	2547	—	4896	686
Storage areas	43	4289	1196	1208	4899	56
Fast-food outlets	18	881	526	320	1592	151
Clothing stores	14	661	393	164	755	142
Restaurants	11	582	298	190	625	84
Kitchens	8	553	314	161	602	149

Figure 8. Example of fire load density data obtained and analysed by Zalok et al. [14]. The data of restaurants is analysed further using a gamma distribution model[2].

With the known energy Q_{unit} that a single fire load unit can release in the fire and the total energy of the space considered with floor area of A_f, $Q_{\mathrm{tot}} = A_f \times q''$, the number of fire load units becomes

$$N_{units} = Q_{tot} \Big/ Q_{unit} = \frac{A_f \cdot q''}{\sum_{k=1}^{K} \chi_k \cdot \Delta H_{c,k} \cdot M_k} \tag{3-2}$$

---

[2] The most frequently used statistical models for fire load densities are the lognormal distribution and the Gumbel distribution. However, the essential feature that the model must capture is the skewness of the distribution. Regarding this basic requirement, e.g., gamma or Weibull distributions are equally proper as lognormal or Gumbel distributions. There is an additional advantage with gamma or Weibull distributions: it is easy to add a lower or upper level cut-off value (depending on whether high or low values are dangerous). This feature can be used to cut away unreasonably low values of fire load density.

3.2.3 Propagation of fire to other igniting objects

The most common modes that a fire of some single unit may propagate to other igniting objects are

- heating due to direct heat radiation from the flames of the first ignited item
- heating due to the build-up of hot smoke layer in the space.

According to Babrauskas [15], some secondary items may ignite readily at 10 kW/m^2 heat exposure while others may sustain 40 kW/m^2, see Figure 9.

The most important issue in fire spread to other items is that such fire may grow very large. Therefore, the occurrence of such fire must be kept very unlikely by suitable fire safety measures. Here the high reliability and efficiency of the automatic suppression systems are utmost important.

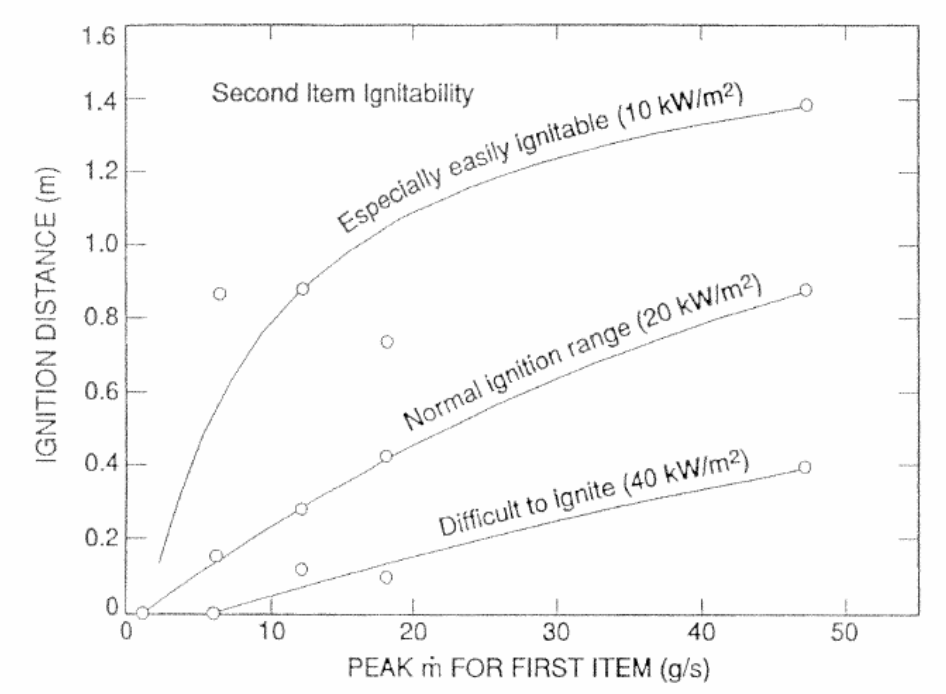


Figure 9. Relationship between peak mass loss rate and ignition distance for various ignitability levels (radiant flux) [12, 15].

3.2.4 Influence of first-aid extinguishers

In practice, first-aid extinguishers have a significant effect on the fire development as a notably fraction of fires is extinguished by first-aid extinguishers before they grow to an extent posing significant threats.

3.2.5 Influence of fire detection systems

The operation of fire detection systems can be modelled by using a model that describes heat exposure and the consequent heating of the sensor. It should be noted that this approach is applicable also to smoke detectors because in the initial phases of the fire there is one-to-one correspondence between the smoke density and the temperature rise [12, 16].

3.2.5.1 Heat sensors

The heating of a sensor can be described by the following equation:

$$\frac{dT_d}{dt} = \frac{1}{\tau}\left(T_g - T_d\right) \tag{3-3}$$

where T_d is the sensor temperature [°C], T_g is the temperature of the hot gases and flames from the fire [°C], and τ is a time constant [s]

$$\tau = \frac{RTI}{\sqrt{u}} \tag{3-4}$$

where RTI [$m^{1/2}s^{1/2}$] is the response-time index of the sensor, and u is the flow velocity of the hot gases. The simplest method to assess T_g and u is to use Alpert's [17] correlations

$$T_g - T_\infty = \frac{16.9 \cdot \dot{Q}^{2/3}}{H^{5/3}}, \text{ r < 0.18H,} \tag{3-5}$$

$$T_g - T_\infty = \frac{5.38 \cdot \left(\dot{Q}/r\right)^{2/3}}{H}, \text{ r} \geq \text{0.18H,} \tag{3-6}$$

$$u = 0.96 \cdot \left(\frac{\dot{Q}}{H}\right)^{1/3}, \text{ r < 0.15H,} \tag{3-7}$$

$$u = \frac{0.195 \cdot \dot{Q}^{1/3} \cdot H^{1/2}}{r^{5/6}}, \text{ r} \geq \text{0.15H,} \tag{3-8}$$

where T_∞ [°C] is the ambient temperature (typically 20 °C), $\dot{Q}$ is the heat release rate (HRR) [kW], H [m] is the height from the fire origin to the ceiling, and r [m] is the horizontal distance from the fire centre line. In practice, the sensor temperature development is easy to solve by the forward Euler integration method:

$$T_d(t_k + t_{k+1}) = T_d(t_k) + \frac{\sqrt{u(t_k)}}{RTI}\left(T_g(t_k) - T_d(t_k)\right)\left(t_{k+1} - t_k\right) \qquad (3\text{-}9)$$

The sensor activates when its temperature reaches the activation temperature T_{act} of the sensor. When RTI index, T_{act} and r are known, the sensor activation depends on the HRR growth time factor t_g and the distance between the fire origin and the ceiling H.

3.2.5.2 Smoke detectors

Modelling a smoke detector as a fast low-temperature-activation heat sensing device

A smoke detector can be modelled as a fast low-temperature-activation heat sensing device. For smoke detectors, the following parameter values are typical:

- RTI = 50, …, 150 $m^{1/2}s^{1/2}$ [18]
- T_{act} = 57 °C or higher [19]
- r = 0, …, $r_{\max,h}$, where $r_{\max,h} \approx \sqrt{\left(\sqrt{A_h}/2\right)^2 + \left(\sqrt{A_h}/2\right)^2} \approx 4$ m is the maximum distance of the heat detector from the fire determined by the maximum protection area ($A_h = 30\ m^2$) of a heat detector [19].

For heat detector, the following parameter values are typical:

- RTI = 5, …, 10 $m^{1/2}s^{1/2}$ (uniform distribution) [12]
- $T_{act} = T_\infty + \Delta T_s$, where $\Delta T_s \approx 13, \ldots, 20$ °C (applicable distribution is the uniform distribution or the more elaborated one given in [16])
- r = 0, …, $r_{\max,s}$, where $r_{\max,s} \approx 5.5$ m is the maximum distance of the heat detector from the fire determined by the maximum protection area ($A_s = 60\ m^2$) of a heat detector [19].

Modelling a smoke detector using smoke density

A physically more sound approach is to model a smoke detector as a device that actuates when the smoke density reaches some threshold value. Heskestad [20] proposes a model that is similar to that governing heat sensing device operation:

$$\frac{dY_c}{dt} = \frac{1}{\tau_s}\left(Y_e(t) - Y_c\right) \tag{3-10}$$

where Y_c is the mass density inside the device, Y_e is the smoke density within the fire gases and the time constant $\tau_s = L/u$ [s] depends on the characteristic length L of the device. The value suggested by Heskestad is $L = 1.8$ m.

Cleary et al. [21] have developed a different model according to which

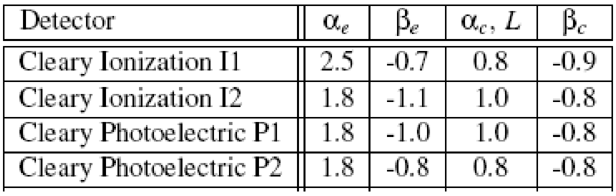
$$\frac{dY_c}{dt} = \frac{Y_e(t - \delta t_e) - Y_c(t)}{\delta t_c} \tag{3-11}$$

where

$$\begin{aligned} \delta t_e &= \alpha_e \cdot u^{\beta_e} \\ \delta t_c &= \alpha_c \cdot u^{\beta_c} \end{aligned} \tag{3-12}$$

Typical values of the parameters α_e, β_e, α_c ja β_c for smoke sensors with different operating principles are show in Table 5.

Table 5. Typical values of the parameters α_e, β_e, α_c ja β_c for smoke sensors with different operating principles [22].



Detector	α_e	β_e	α_c, L	β_c
Cleary Ionization I1	2.5	-0.7	0.8	-0.9
Cleary Ionization I2	1.8	-1.1	1.0	-0.8
Cleary Photoelectric P1	1.8	-1.0	1.0	-0.8
Cleary Photoelectric P2	1.8	-0.8	0.8	-0.8

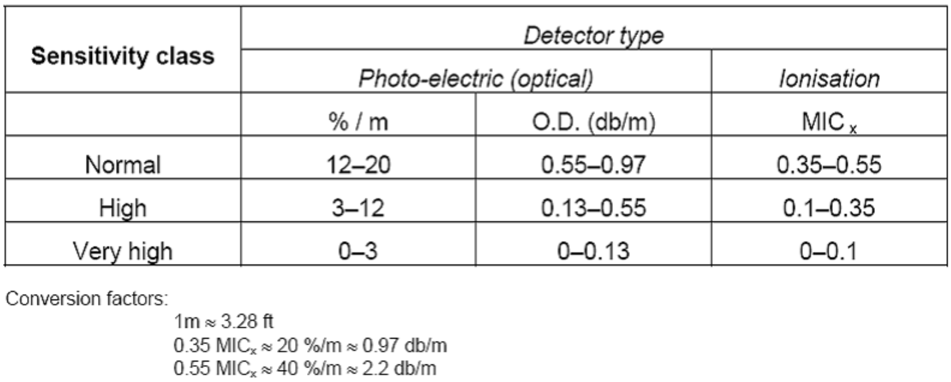
Both Heskestad and Cleary et al. models are implemented in the FDS version 5 [23].

Time of fire detection Δt_{det} is the time delay required to generate sufficiently high smoke concentration inside the detector:

$$Y_d\left(\Delta t_{\text{det}}\right) = Y_{act} \tag{3-13}$$

where Y_{act} is the smoke density when the device actuates. These values are shown in Table 6. It should be noted, that the FDS5 fire simulation program uses a default value of 3.28 %/m, which corresponds to a value of 1 %/foot, which is convenient to American users. Hence, it advisable to excersice some critical consideration regarding this value.

Table 6. Actuation smoke densities form different types of smoke detectors [12].



Sensitivity class	*Detector type*		
	Photo-electric (optical)		*Ionisation*
	% / m	O.D. (db/m)	MIC $_x$
Normal	12–20	0.55–0.97	0.35–0.55
High	3–12	0.13–0.55	0.1–0.35
Very high	0–3	0–0.13	0–0.1

Conversion factors:
1m ≈ 3.28 ft
0.35 MIC_x ≈ 20 %/m ≈ 0.97 db/m
0.55 MIC_x ≈ 40 %/m ≈ 2.2 db/m

3.2.6 Influence of automatic fire suppression systems

Properly designed, constructed and maintained automatic suppression systems [24] shall be able to detect the fire and activate accordingly. After activation, the system shall either suppress the fire or keep it under control so that the fire can be extinguished by other means. The relevant physical mechanisms are

- slowing down the fire growth
- reduction of the peak heat release rate
- cooling of the gases flowing in the fire plume and consequently reduction of the heat exposure from the hot smoke layer
- reduction of the direct heat exposure from the burning item to other items.

As a rule on thumb, one may assume that if there is an automatic suppression system that functions as designed, fire remains limited to the first igniting item.

3.2.6.1 Empirical models

Up to the recent years, simple correlations used to reduce the heat release rate were the only available models to account for the effect of the automatic suppression system. The systems addressed are sprinkler systems. As the formulae do not include the droplet size, the correlations are not applicable to water mist systems where the enhanced suppression power is principally due to the influence of the small size of droplets. Although water mist has mainly replaced sprinkler systems, below we recapitulate briefly some of the empirical sprinkler models.

In experiments of the influence of the sprinkler water spray on the development of the fire, the sprinkler water delivery rate has usually been dimensioned so that the sprinkler is able to cut the growth of the heat release rate (HRR) and turn it into decay. The model frequently used on the sprinkler effect is

$$\dot{Q}_{SPR}(t) = \dot{Q}(t_{act}) \cdot \exp(-k \cdot (t - t_{act})), \tag{3-14}$$

where t_{act} is the sprinkler activation time, $\dot{Q}(t_{act})$ is the HRR at time t_{act}, and the constant k [s^{-1}] depends on the water mass flux $\dot{m}''$ ($\mathrm{kgm}^{-2}\mathrm{s}^{-1}$). Commonly used models for k are those of Evans [25], Hamins & McGrattan [26] and Yu et al. [27]:

$$\text{Evans: } \frac{k}{\mathrm{s}^{-1}} = 0.33 \cdot \left(\frac{\dot{m}''}{\mathrm{kgm}^{-2}\mathrm{s}^{-1}} \right)^{1.85}, \tag{3-15}$$

$$\text{Hamins \& McGrattan: } \frac{k}{\mathrm{s}^{-1}} = 0.19(6) \cdot \frac{\dot{m}''}{\mathrm{kgm}^{-2}\mathrm{s}^{-1}} - 0.0007(66), \tag{3-16}$$

$$\text{Yu et al. } \frac{k}{\mathrm{s}^{-1}} = 0.18 \cdot \frac{\dot{m}''}{\mathrm{kgm}^{-2}\mathrm{s}^{-1}} - 0.01. \tag{3-17}$$

The experiments are typically carried out in such a way that the sprinkler activation is triggered when HRR has reached a steady state value (the value $\dot{Q}(t_{act})$). If the sprinklers would have been triggered in the phase when HRR was still growing, the above model may give too optimistic result as it predicts that the fire growth would abruptly be stopped and turned into an exponential decay. A more conservative model on the sprinkler effect that is in accordance with the experimental data reads

$$\dot{Q}_{SPR}(t) = \dot{Q}(t) \cdot \exp(-k \cdot (t - t_{act})). \tag{3-18}$$

In this model, there is no sudden cut-off and decay of HRR, but HRR will grow – yet on a slowing-down rate – also after the sprinkler activation, and it will take some water-flux-dependent time delay after which the sprinkler turns HRR into decay.

3.2.6.2 Expert-judgement method used in some ashore applications

Besides the above-mentioned empirical correlations, there is an expert-judgement based approach that is fairly frequently used in ashore applications of FSE design. This very simplistic model is as follows:

1. Calculate the time t_{act}, e.g., using the formulae given in 3.2.5.1
2. Look at what is HRR at the time t_{act}, $\dot{Q}(t_{act})$
3. The design HRR, $\dot{Q}_d$, is obtained by doubling this value $\dot{Q}_d = 2 \times \dot{Q}(t_{act})$, and the fire is assumed to burn on the design HRR until the end of calculation.

3.2.6.3 Simulation of the performance of suppression systems

During the couple of recent years, it has become possible to simulate the influence of performance of suppression systems. Here we consider only the water-based systems. The present situation (May 2009) can be summarised as follows:

- At present, modelling of sprinklers is quite well mastered by research institutes such as NIST/USA or VTT/Finland, only to mention some. Since a considerable amount of validation has already been done, the prediction of sprinkler performance stands on fairly solid ground. It can be foreseen that sprinkler modelling will become a routine task applied in engineering offices within a couple of years.
- Modelling of water mist is possible, but at present very challenging and time consuming. It is under intense research in most advanced research institutes to provide practically applicable methods.

3.2.7 Influence of the ship staff

The influence of the ship staff depends on the time when it arrives at the fire scene and is ready to start fire fighting. These issues have been addressed in the cabin fire analysis of Karhula [28].

There is another issue that may become important especially in fires where the performance of automatic suppression systems is inadequate. It is the ability of the staff to extinguish the fire. This issue has been quantified in the NFPA Fire Protection Handbook [29] as curves on the ability of different kinds of fire fighting units to extinguish a fire of a given size. The units considered are

1. an average person with an extinguisher
2. a trained fire brigade
3. an average fire department
4. the strongest fire department.

The results are presented as extinguishing failure (or success) probabilities versus the area of flame/heat. They are reproduced in Figure 10. The format of the presentation of the data is not among the easiest for adaptation of the data in calculations. Thus we have read some data points from the curves and converted them to SI-units; these results are given in Tables 7–10 and Figure 11. If we consider, e.g., that an event is “likely” if its probability is higher than 90 %, it can be seen that

- “an average person with an extinguisher” is likely to be able to extinguish a fire of size of ~ 2 m^2
- “a trained fire brigade” is likely to be able to extinguish a fire of size of ~ 5 m^2
- “an average fire department” is likely to be able to extinguish a fire of size of ~ 50 m^2
- “the strongest fire department” is likely to be able to extinguish a fire of size of ~ 100 m^2.

Tentative analysis of the data using a 3-parameter gamma distribution is shown in Figure 12. The distribution parameters obtained in least-squares fitting are displayed in the figures.

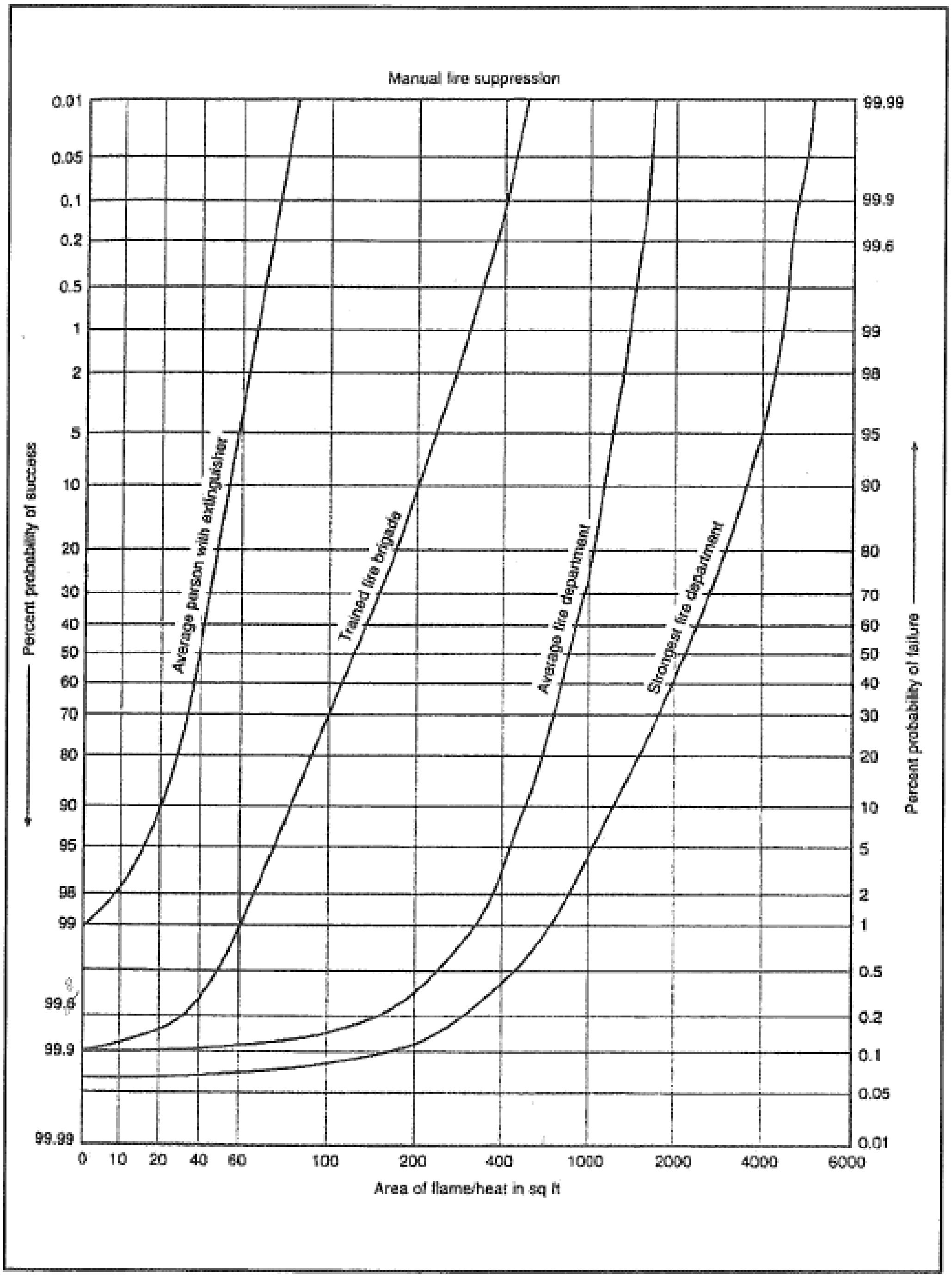


Figure 10. NFPA curves for fire-fighting units' extinguishing failure (and success) probability [29].

Table 7. Extinguishing failure probability for an average person with an extinguisher read from Figure 10.

AVERAGE PERSON		
area (ft^2)	**area (m^2)**	**P[fail]**
60	5.57	96.702
50	4.64	79.360
40	3.72	54.740
30	2.79	18.461
20	1.86	9.046
15	1.39	3.84
10	0.93	2.08
5	0.46	1.55

Table 8. Extinguishing failure probability for a trained fire brigade read from Figure 10.

TRAINED FIRE BRIGADE		
area (ft^2)	**area (m^2)**	**P[fail]**
400	37.16	99.894
200	18.58	90.204
100	9.29	30.646
60	5.57	1.149
40	3.72	0.267
20	1.86	0.14
10	0.93	0.11

Table 9. Extinguishing failure probability for an average fire department read from Figure 10.

AVERAGE FIRE DEPARTMENT		
area (ft^2)	**area (m^2)**	**P[fail]**
1500	139.34	99.043
1000	92.89	71.679
400	37.16	2.995
200	18.58	0.292
100	9.29	0.130
60	5.57	0.1
40	3.72	0.10
20	1.86	0.09

Table 10. Extinguishing failure probability for the strongest fire department read from Figure 10.

STRONGEST FIRE DEPARTMENT		
area (ft^2)	**area (m^2)**	**P[fail]**
5000	464.47	99.931
4000	371.58	94.7
3000	278.68	73.5
2000	185.79	44.8
1500	139.34	14.6
1000	92.89	4.0
400	37.16	0.36
200	18.58	0.10
100	9.29	0.07
60	5.57	0.059

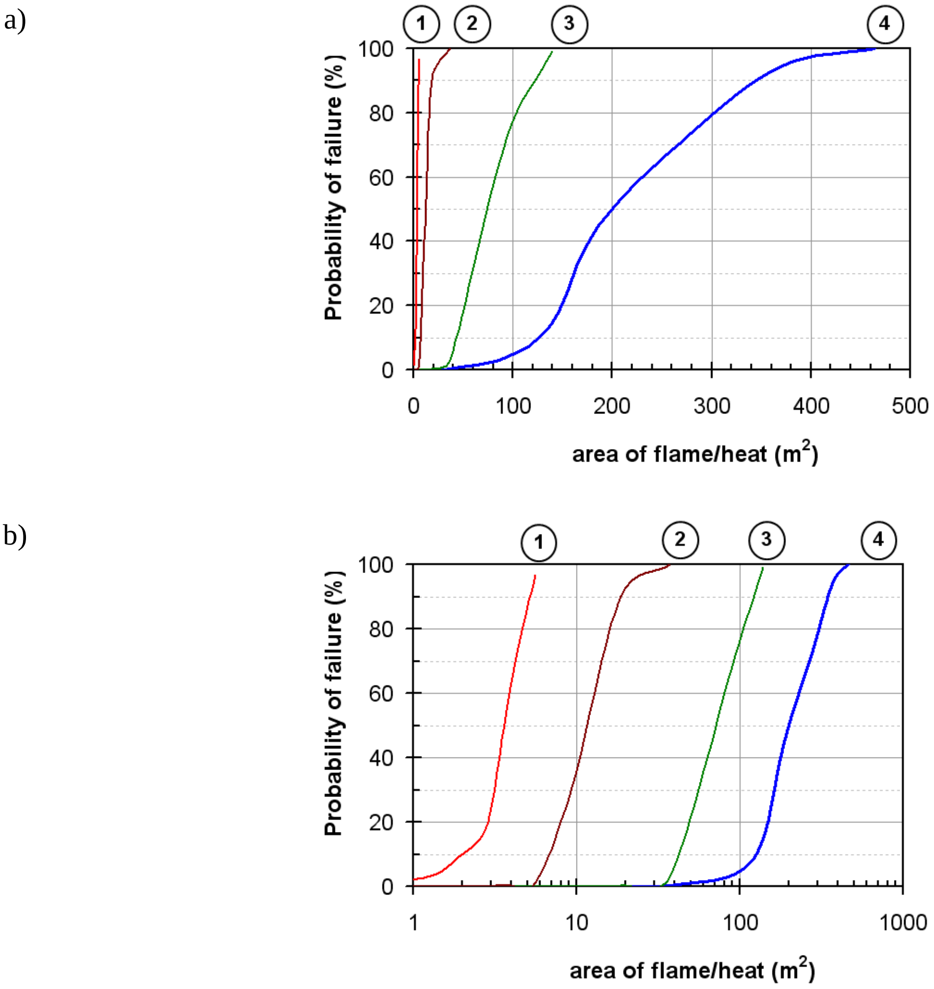


Figure 11. The NFPA curves for fire-fighting units' extinguishing failure (and success) probability plotted in SI-units using the data given in the Tables 7–10: a) linear scales and b) logarithmic abscissa.

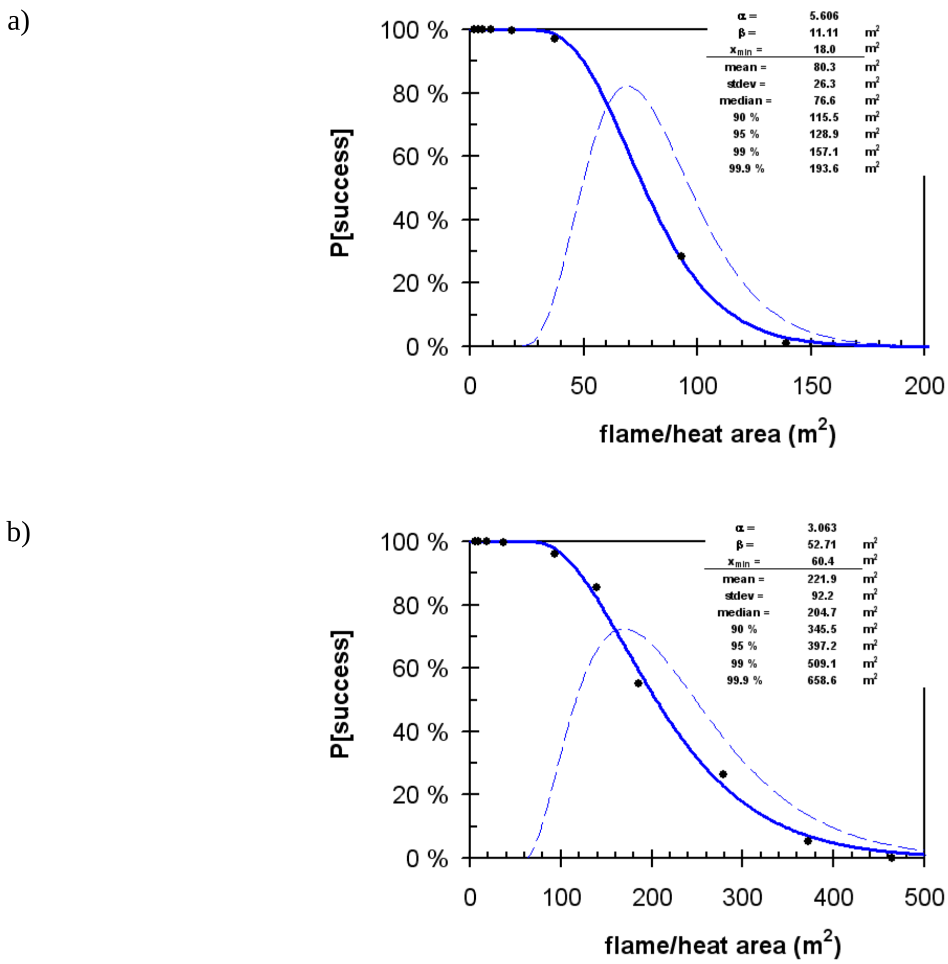


Figure 12. Analysis of the fire extinguishing success probability of a fire department: a) an average fire department and b) the strongest fire department.

3.3 Fire statistics and fire frequencies

This section presents ship fire statistics and fire frequencies found in a short literature search. The sources are briefly presented together with main results. Specific numbers are presented in tables according to source in Appendix A. Fire frequencies were found per ship-year for fires of different severity, for different types of ship and per distance sailed, as well as fatality frequencies due to fire, distribution of fire origin, location of the ship when fire originated and time required to extinguish fire. A rough comparison with building fire frequencies is given.

3.3.1 Ship fire statistics

The IAEA research [30] considers risk of accidents during maritime transport of radioactive material. Although it concerns transport on four different types of ships: container ships, roll-on/roll-off (Ro-Ro) ships, general cargo (break-bulk) ships or purpose-built ships; ship accident data covering all types of ships were collected and analysed for the period between 1978 and 1997. The accident statistics were taken mainly from the Lloyd’s database and the Marine Accident Investigation Branch (MAIB) of the UK. A short description of the databases is given in the following.

Lloyd’s databases

The IAEA report refers to two types of databases available from Lloyd’s:

- all incidents reported to the Lloyd’s Maritime Information Services (LMIS), and
- all total losses reported to the Lloyd’s Register of Shipping.

The Lloyd’s Casualty Database is compiled by Lloyd’s Maritime Information Services (LMIS), records on the average 1000 serious casualties per year, and includes [31]

- all reported serious casualties, including total losses, to all propelled sea-going merchant ships in the world of over 100 GRT[3] from 1978
- all reported incidents (i.e. serious and non-serious) to tankers, including chemical tankers, combination carriers and gas carriers, since 1978
- all ships broken up or otherwise disposed of not consequent on casualty from 1978.

Serious casualties are defined involving

- total loss
- breakdown
- flooding of any compartment
- structural, mechanical or electrical damage requiring repairs before the ship can continue trading.

Total losses correspond to ships which “as a result of being a marine casualty, have ceased to exist, either by virtue of the fact that the ships are irrecoverable or have subsequently been broken up”.

A casualty is defined as fire/explosion when fire/explosion is the first event reported (except where the first event is a hull/machinery failure leading to fire/explosion) [30].

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[3] GRT = Gross Register Tonnage, GT = Gross Tonnage, volume of the ship, in units of 100 cubic feet = 2.83 m^3. GRT equals GT less some specified spaces.

The Marine Accident Investigation Branch (MAIB), UK

The data from the MAIB database deal with UK registered ships of 100 GT or more, corresponding to a fleet of about 1100 merchant ships (in the 1990s). The database includes most of the events leading to insurance compensation. The events correspond to the following criteria:

- loss of life or major injury
- ship lost or materially damaged
- ship stranded or having collided
- major injury or material damage to the environment.

The classification of the accidents, e.g. fire/explosion, is similar to the one defined by the Lloyd’s.

According to the IAEA report, the frequencies obtained from the MAIB statistics could be used for determining the occurrence of initiating events, but are not necessarily representative of fires severe enough to be able to endanger packages of radioactive material.

International Maritime Organization

This database (Fire Casualties Records) includes all fires reported to IMO by all member countries. The selection criterion is: any fire which highlights a possible deficiency, inconsistency, etc. in the Safety of Life at Sea Regulations (SOLAS Convention).

Bureau Véritas

As Bureau Véritas follows up on about 10–20 % of the world fleet, a database was created for severe fire accidents (fire leading to total losses or recovery of the ships after repair). Three categories of ships were selected from this database as they seemed to be representative of the radioactive material transports (general cargo, container, Ro-Ro/passenger).

Results from the IAEA report are presented in Table A1 , Table A2, Table A8, Table A13, Table A14 and Table A15 of Appendix A. IAEA references are mentioned after the tables only the first time they occur. Fire frequencies per ship-year, grouped according to the severity of the event, are presented in Table A1. As stated above, frequencies from MAIB statistics are denoted as “all fires”, while frequencies from Lloyd’s statistics are denoted severe. The IAEA report does not exactly discuss the distinction between “all fires” and “severe fires”, but it is pointed out that the severe fire data originates from relatively severe accidents, as only events leading to deaths, injuries and/or considerable commercial losses were included in the records. A most interesting feature in the MAIB data from 1990–1996 is that the frequency declined steadily and markedly from 1990 (25.6×10^{-3} fires/ship-year) to 1996 (1.9×10^{-3} fires/ship-year).

The study by Kay et al. on world fleet ships, data from Lloyd’s 1984–1993 (Table A1), aimed to estimate the number of incidents with a potential to threat an irradiated nuclear fuel flask, carried as a cargo item. Oil tankers and liquefied gas carriers were excluded as unsuitable to carry flasks, and from the remaining cases 93 engine room fires which spread to the cargo area, or severe fires arising in the cargo hold were identified.

Categories of ships likely to be used to carry radioactive material were extracted from the total loss statistics and fire frequencies per ship type year were calculated as presented in Table A2, with data from Lloyd’s and Bureau Véritas databases. The Bureau Véritas figures are overall somewhat higher than Lloyd’s. It is noted in the report that the Bureau Véritas data relate to an earlier period (1978–1988 compared with Lloyd’s 1994–1997) and that the number of fires varies significantly from year to year. Considering that the MAIB frequencies show the same trend, it is suggested in the report that fire frequencies may be diminishing over time. This may be due to better standards of equipment and/or operation of ships.

The distribution of the origin of fire is presented in Table A8. The fires originated mainly in the machinery room, and secondly in the quarters.

Fire frequencies per ship nautical mile (nmi) or port call are presented in Table A13. Location of the ship when the fire occurred is presented in Table A14.

The duration of fire was seldom mentioned in the databases, but some values were available from an UK analysis of IMO and MAIB fire data, and times required to extinguish fires are presented in Table A15. It is underlined that this corresponds to only 20 accidents, all belonging to the severe fire accidents class, and cannot be considered representative.

It is concluded in [30] that per year of sailing, ship fire frequencies range from 10^{-2} for fires of any severity to 2×10^{-3} for fires that start in or spread to cargo holds, and to 8×10^{-4} for fires that lead to the total loss of the ship. Given that a typical ship sails 60 000 nmi per year, the frequency of fires that lead to the total loss of the ship is about 10^{-8} per nmi. The frequency of fires of any severity is about 2×10^{-7} per nmi which agrees well with the value of 10^{-7} per nmi sailed developed by examination of fire data by sailing region. The examination showed that fire frequencies depend very little on sailing region or traffic density and found that port fire frequencies were about 5×10^{-5} per port call.

It is pointed out in [30], that the databases used vary in terms of the number of ships, type of ships, definition of accidents, numbers of recorded incidents and time periods covered. Thus, the interpretation of the results from these databases gives a wide range of probabilistic information. It is also noted that the derived probabilistic data stem from relatively severe accidents, since only accidents leading to deaths, injuries and/or considerable commercial losses were included in the records. Initiating events or precursors which have resulted in less serious consequences (e.g. successful fire fighting at an early stage) will have higher frequencies than those provided in the tables.

Vanem and Skjong [32] present fire and fire-induced fatality frequencies for passenger ships based on data from Lloyd’s register – Fairplay, supplemented with data from other sources (Table A3). Separate results were presented for RoRo passenger ships (RoPax) and cruise liners. Fires on ships undergoing repair were omitted as well as fires categorised as non-serious. Frequencies for cruise liners were about six times higher than for RoPax vessels. According to the authors, this corresponds with previous studies on passenger ship fires performed by Det Norske Veritas (DNV) and documented in internal DNV reports. Their results relating to origin of fire are presented in Table A9. Engine room is the most probable origin of fire.

Vanem and Skjong point out that fire accidents leading to fatalities are rare, giving a weak statistical base. They therefore merged RoPax and cruise liner data to strengthen the foundation for estimates, and considered potential loss of lives during evacuation because of fire. The database contained six cases where lives were lost due to ineffective evacuation giving an estimate of 1.4×10^{-2} loss of lives per ship-year. This concerns the risk associated with evacuation because of fire and not the risk of fire itself.

Nilsen [33] presents Det Norske Veritas (DNV) fire statistics from 1992–2004. Fire frequencies per ship type are presented in Table A4 and origin of fires is presented in Table A10. The reported fire trend was reported to be lower for the period 1998–2004. Also here is noted that small fires are often not reported, and it is estimated that 5–15 % of the DNV fleet has a minor (not reported) fire every year.

The large DNV report prepared by Spouge [31] considers safety assessment of RoPax vessels in north-west Europe using Lloyd’s casualty database compiled by LMIS. Ships over 1000 GRT and serious casualties were considered. Fire frequencies from this study are presented in Table A5 and frequencies of origin of fire in Table A11. Frequencies of fire/explosion on all UK ships over 100 GRT during 1979–1988 and 1990–1994 were also presented (Table A6). The grouping of casualties in these two UK statistics differs somewhat from each other, but it is stated that comparing the two sets of figures in the table, no significant trend in fire/explosion frequency is shown. This apparently refers to the average figures and not to any trend within the time periods. The statement is thus not in conflict with the IAEA observation of declining annual fire frequencies during the 1990’s. A comparison between RoPax in north-west Europe and worldwide shows that the total loss frequency is higher and the serious fire frequency is lower in the world-wide statistics. It is suggested in the report that this could reflect lower standards of fire protection or under-reporting of less serious events world-wide.

Kaneko [34] gives frequency of fatalities due to fire on passenger ships (Table A7) using data from Lloyd’s Marine Intelligence Unit (LMIU) ship characteristics and casualty database. The statistics were used in a trial calculation using a safety assessment model proposed in the paper.

Karhula [28] obtained fire frequencies for ships carrying passengers using incident reports from the IMO GISIS Maritime Casualties and Incidents database. Results are presented in Table A12.

3.3.2 Building fire statistics

Building fire frequencies are presented based on statistics from three databases, the Finnish PRONTO database (Statistics system of Finnish rescue services), London Fire Brigade’s Real Fire Library and a Swiss database of the GVB (Gebaude Versicherung des Kantons Bern), all differing somewhat in sampling.

Tillander [35] presents fire frequencies for buildings based on statistics from the Finnish national accident database PRONTO during the period 1996–2001. The PRONTO database contains information on all accidents for which the public fire department has been alarmed. Building ignition frequency depends on floor area of the building, and they are presented per floor area and year ($1/m^2a$). As no area information was given in the ship fire frequencies presented above, building fire frequencies were converted to per building-year (1/a) for rough comparison.

Holborn et al. [36] present risk data on fires in workplace premises in London using fire data from London Fire Brigade’s Real Fire Library (RFL). The database contains information from fires collected by the fire investigators of London Fire Brigade. Fire investigators are automatically alerted on the occurrence of

- fires where four or more fire engines are sent to the scene of the fire
- fires where people are reported to be inside the burning building when the call to the brigade is made.

Other considerations requesting fire investigation are: human (e.g. fatalities, serious injuries, and evacuations), operational (e.g. suspicious source of ignition), fire safety (e.g. automatic fire detection, fire suppression), and fires of special interest (e.g. new materials and construction techniques). Data has been collected since 1994 into the library at a rate of approximately 5 000 incidents per annum representing about 20–25 % of the primary fires attended by London Fire Brigade each year. More than 27 000 separate incidents (December 2000) are recorded in the database. Fires in residential dwellings were excluded in the Holborn study because the focus was on the workplace.

Fontana et al. [37] presents a survey of all building fires in the canton of Berne, Switzerland, for the period 1986–1995. The study is based on the database of the GVB (Gebaude Versicherung des Kantons Bern), the public building insurance company of the canton of Berne. As the insurance system is monopolistic, mandatory and without excess, a complete set of data on the fire losses (even very small losses) is available from the files of the public building insurance company. The insurance covers the value of the building structure including installations, decorations and linings fixed to the building structure but not the contents (e.g. a lamp screwed to a wall or the ceiling is covered while a lamp standing on a desk is not). The database includes many more fires than the fire brigade reports because even small fires are reported which did not need fire brigade attention. During the period from 1986 to 1995, 39 104 fires were reported to GVB.

Fire frequencies from these three studies are presented in Table A16 for all buildings and for some building categories with functions resembling those of ships, i.e. dwelling, industrial, shop and office.

These databases differ in data collection as PRONTO includes all fires reported to the public fire department, RFL deals with fires requiring inspection by a fire investigation unit, and GVB contains all fires with some kind of loss. Holborn et al. state that the figures from RFL data give in some sense frequencies for ‘significant’ fires. The grouping of buildings differ also somewhat. The sample difference is reflected in overall higher frequencies for Berne canton. The difference in frequencies from PRONTO and RFL is not as clear.

The significance of how to express the frequencies is seen in Table A16, when frequencies per building-year are compared to frequencies per m^2-year. The ratio of Finnish frequency to London frequency is consistently lower expressed in 1/m^2-year than expressed in 1/building-year. According to Tillander, this indicates that the considered buildings in London have on the average a smaller floor area than the buildings in the PRONTO database covering whole Finland, giving higher frequencies per floor area.

Fire loss distributions are skewed [38], with long tails. According to Lindblom [39], in her study on the distribution of fire loss in Finland during 1996–2000, the number of large fires in Finland is only about 1 % of the total number of fires, although they correspond to about 60 % of all economic fire loss. A fire accident was denoted as large at the time period studied if the value of the damage exceeded 1.0 million FIM (ca. 168 k€). During 1996–2000, 334 large fires were registered. Combining with the 1999 total number of buildings, 1 290 955 [35], a large fire frequency 6×10^{-5} 1/building-year is obtained.

3.3.3 Conclusions

This short literature survey presents published ship fire frequencies based on different casualty database statistics. No attempt was made to investigate the databases beyond the published results, other than quoting database features presented in the reviewed reports. As already mentioned in the IAEA conclusions [30], the statistics behind the fire frequencies are very varying leading to scatter in results. Comparison between fire frequencies at sea and ashore are in addition complicated by the fact that the appropriate way to express fire frequencies is per unit of floor area and time, and the ship fire frequencies found were expressed as per ship-year. These sources of inaccuracy should be kept in mind considering the order of magnitude comparisons presented below.

Fire frequencies

A rough order of magnitude comparison shows that, from statistics for ‘all ships’ and ‘all fires’, frequencies are of order 10^{-2} per ship-year. ‘Serious fires’ frequencies are of order 10^{-3} per ship-year and fires leading to total loss generally of order 10^{-4} per ship-year.

Frequency for all building fires in Finland was 2.5×10^{-3} per building-year during 1996–2001. Statistics from ‘significant’ fires on workplaces in London during 1996–1999 give frequencies of $1.7–3.8 \times 10^{-3}$ per building-year except for hotels 6.7×10^{-2} per building-year. Fire frequency for all fires in Berne canton in Switzerland during 1986–1995 was 1.2×10^{-2} per building-year. These frequencies seem to be roughly at the same level as fire frequencies at sea.

Serious fire frequencies for passenger/RoPax vessels were in the range 1.6×10^{-2} to 1.9×10^{-3} per ship-year. Some of the reported fire frequencies for passenger ships, order 10^{-2} per ship-year, are larger than frequencies for other ship types. Definite conclusions are still not easy to make due to the uncertainty concerning the information in the databases.

Comparing passenger ship fire frequencies to fire frequencies in Finland during 1996–2001 for dwellings, 1.3×10^{-3} per building-year, and for shops, hotels and restaurants, 3.2×10^{-3} per building-year, frequencies at sea and ashore are roughly of the same order of magnitude. London fire frequencies indicate the same.

Severity/fire loss

Although no probability distributions on fire frequencies or fire loss were given in the reviewed reports, an order of magnitude comparison is made between the ratios of ‘severe’ fire to ‘all fire’ frequency at sea and ashore. Dividing the frequencies for ‘total loss’ and ‘serious’ fire with frequency for ‘all fire’ gives a ratio of 1–10 % of all reported fires at sea, (total loss 1–2 %, serious fire 9–11 %).

Lindblom [39] gives percentages for large fires as generally 5–10 % of the total number of fires and for the specific case Finland during 1996–2000, about 1 %. Similar numbers are given by Fontana et al. [37] for Berne canton during 1986–1999: 2 % of the fires caused losses larger than 100 000 CHF and 0.17 % caused losses larger than one million CHF.

Although comparison between the ‘total loss’ at sea defined as above and fires causing losses larger than a specified amount ashore include uncertainties, the ratio of ‘large fires’ to ‘all fires’ at sea and ashore seems to be roughly of the same magnitude.

Origin of fire

The current origin of ship fire was engine room, 60–67 % of all cases. Due to the strong concentration of fires to the engine room area, comparison with distributions of fire origin ashore is not reasonable. Fire frequencies for fires originating in accommodation areas were in the range $2 \times 10^{-3} - 1.4 \times 10^{-4}$ per ship-year.

3.4 Cabin fire on a passenger ship

Traditionally adequate fire safety on a passenger ship has been indicated by different fire tests. It is also possible to define satisfactory fire safety level using performance based design. Since 2001, performance based fire safety engineering has also been accepted in passenger ship fire safety design in addition to component based design. This section examines the international fire safety regulations for passenger ships and addresses the criteria for acceptable design for structures and furniture. This section proposes a way to create fire safe cabins by using a quantitative method for risk assessment. A performance based fire safety design method is created in order to evaluate fire scenarios in cabins. Extinguishment possibilities for different fire scenarios are calculated, and damage caused by fire is evaluated.

Passenger ship cabin fire scenarios are defined using the GISIS accident database of IMO. Also ignition frequency is calculated from statistics. Fire on a passenger ship cabin occurs once in every five years. Serious damages are caused on a passenger ship by fire about 3.0×10^{-4} times per year. A simulation tool is used to evaluate how cabin fires can increase depending on the cabin’s materials, furniture and luggage. Probability for each scenario is calculated and fire damages are evaluated for each scenario. Damages caused by fire and ignition frequency are combined together to define fire risk in cabins.

Quantitative fire risk analysis is used to find out the probability of the fire spreading out of the cabin to the corridor or to an adjacent cabin. Time dependent event tree method is used together with the fire simulation tool to make the risk analysis. Fire development is a function of time and the time dependency is solved by means of simulation. Heat release rate curve is divided into time intervals and extinguishment attempts are evaluated using an event tree at each time interval separately. All event trees at each time interval are finally gathered together to construct the risk analysis.

This section provides an effective method to evaluate fire risks in new ship cabin solutions. The method is easy to expand further to evaluate other spaces on a passenger ship. Improving fire safety is more efficient when all the key parameters related to fire growth and active fire suppression systems are known and quantified.

This section is based on the Master's thesis "Risk Based Specification of Cabin Fire in Passenger Ships" by T. Karhula (in Finnish) [28].

3.4.1 International fire safety regulations for passenger ships

Fire safety on a passenger ship is assured by building it using incombustible materials in the hull, superstructure, bulkheads and decks and using fire retardant materials in furnishing. Fire induced damage is minimized by using a fast automated fire detection and sufficient extinguishing methods. Shipbuilding regulations and fire safety rules make sure that a certain minimum safety level is typically reached.

International Convention for the Safety of Life at Sea (SOLAS), as amended by resolutions is a regulation collection assuring that passenger ships are built so that fire safety is adequately achieved [40]. SOLAS gives the basic principles how to build a fire safe ship that is accepted by the authorities. There are two ways to fulfil the fire safety criteria on a passenger ship. 1) Adequate fire safety level is reached when all the structures, materials and extinguishing systems pass fire tests, and all different spaces like accommodation premises, the engine room and shops are set as regulations define. 2) Sufficient fire safety level is achieved also if an engineering solution differs from the regulations, but the chosen structural system can be proven to be fire safe by using performance based fire safety engineering design, and showing that the risk of fire damage is acceptably low [3].

3.4.2 Acceptable design

How is an acceptable fire safety engineering design specified on a passenger ship? When does the fire safety design fulfil the criterion of low risk of fire damage? An objective criterion for fire safety level could be set as the number of people killed on board in fire related accidents in a year. Similarly, criteria can be set for property losses. Accident statistics are not any more the only way to check fulfilment of the acceptable design criterion. Fire development and evacuation scenarios can be simulated, and a comparison of the results to the criteria can be instantly made.

The most important acceptance criterion is to limit the risks to people collectively or to individuals on board who may suffer damage due to the effects of fire. Individual risk criteria for death or injury are set using risk levels. Individual risk criterion for death or injury that should be met, as proposed, when safety assessment is carried out for new ships are [3]:

Target individual risk for crew members	10^{-4} annually
Target individual risk for passengers	10^{-5} annually
Target individual risk for public ashore	10^{-5} annually

Individual risk levels include all kinds of accidents. Fire related risks form only a fragment of the presented values.

Acceptance criterion for societal risk can be presented with an F-N diagram. Societal risks are related to society as a whole, which may be affected by the fire accident on a ship. Societal risk acceptance criteria are used to limit the risks of catastrophes affecting many people at the same time. Creating an F-N diagram for a fire in a passenger ship cabin is unnecessary because fire in one cabin concerns only one to four humans. An F-N diagram is produced in section 3.5 concerning a cabin area on a multi-purpose icebreaker.

3.4.3 Method for quantitative fire risk analysis on a passenger ship cabin

3.4.3.1 Scenario description

First the acceptance criterion for the fire safety engineering design is set as clarified above. Then various fire scenarios are listed. Rarity and severity of the scenario are also evaluated. Scenario description includes detailed information of the fire (what burns and where), operation of safety systems (type of fire alarm, water mist actuation temperature, the existence of first-aid extinguishing systems, and the reliability of those systems), and what is threatened in such a fire case. Different scenarios are assumed to be based on accident databases or expert evaluations. It is not possible to find all potential fire scenarios in the cabin. Rare fire incidents that nobody could imagine beforehand can happen. That is why more than one scenario description is needed. Scenarios chosen for detailed discussion should be at least the most common one, and a rare one which can inflict major damage.

3.4.3.2 Scenario quantification

A design fire is a quantification of the fire development in a fire scenario. The design fire describes how rapidly the fire grows, what is the maximum heat release rate, how much smoke the fire produces, and what is the duration of the fire. First, the initial hazardous event is quantified. Then, the chain of effects launched by the initial fire that finally leads to harmful consequences is defined. Fire and its consequences are specified in a fire scenario. Fire evolution is divided to time intervals. Events which can divert the fire evolution to another path of development are checked at each time interval. In an ideal case, all possible fire scenarios can be found and all probabilities for diverging happenings can be calculated. The result is then a comprehensive risk evaluation of a passenger ship cabin fire.

3.4.3.3 Analysis of the fire scenario

Fire simulation is used to predict the fire development in the cabin and the time frame from ignition to a moment when circumstances are developed too dangerous to humans or to structures. The scenario is simulated to find the time when a stimulus created by the fire is enough for a smoke alarm and/or a water mist nozzle to react. The effect of material parameters to the fire development is sorted out by using simulation. Material property distributions like conductivity or heat of reaction are used as input parameters to the simulation. Latin Hypercube sampling is used to pick up the input variables to simulation from the parameter distribution. Simulation results are stored. Input parameter values are compared to simulation results like maximum heat release rate or water mist actuation time. Then all parameters used are sorted so that the parameter which most clearly has an effect to heat release rate development is revealed. Fire safety development investments are easier to allocate knowing the key parameters. Fire safety improvements can have a real influence to safety if those key parameters are kept in mind.

Simulation is used only to model the fire growth and effects to the system caused by the fire. Extinguishing attempts are considered using time-dependent event tree method. As fire is a rare, sudden and dynamic event, the static event tree or fault tree is an inappropriate way to describe the dynamic characteristic of fire propagation and fire induced damage. An event tree is suitable for risk determination when the actual event is static. Using the method of time-dependent event trees, the time dependence of the fire and its consequences can be explicitly evaluated [41].

The basic idea is to analyze the fire incident by using a stochastic design fire. The events investigated during a fire are described with a simulation model. Process variations are modelled as described above. The fire incident is divided to discrete time intervals and at each time interval an event tree is constructed to describe the evolution of the fire. Evolution, in this case, means all possible actions to detect or fight the fire. The determination of the time evolution of the fire can be carried out by employing conditional probabilities or by a state transition process description of the system. That can be described as a Markov process [41].

3.4.3.4 Statistics for a quantitative fire risk analysis

Statistical studies should be carried out to find proper branching probabilities for the time-dependent event tree. Fire tests can reveal the probability for a water mist nozzle failure, a fire drill on a passenger ship helps to formulate a distribution for the quickness of a fire fighting group and so on.

Fire frequency on a passenger ship can be found from accident statistics. Statistics were discussed in more detail in section 3.3. This section contains only results obtained from the IMO Global Integrated Shipping Information System, Maritime Casualties and Incidents (GISIS) accident database. Compilation of data gathered from GISIS is presented in Figure 13.

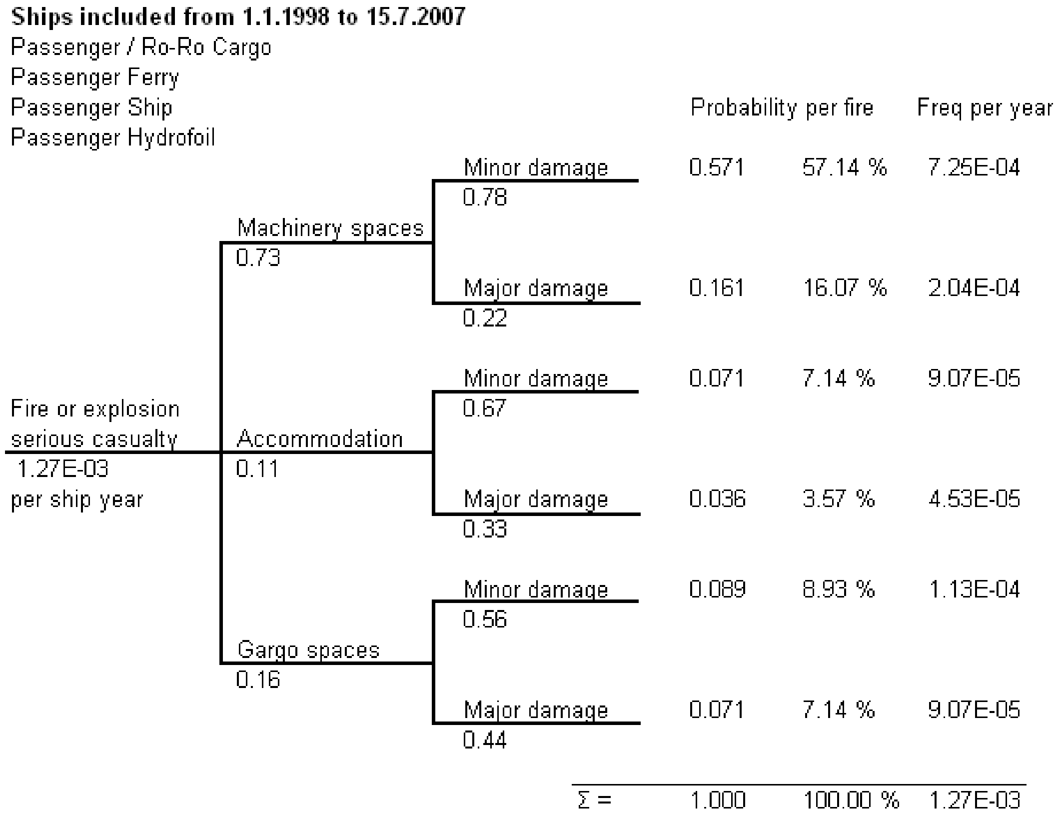


Figure 13. Data from GISIS accident database presented in a tree format.

Only 11 % of all fires on passenger ships start from accommodation area. One third of those fires develop to a state where major damage occurs. Fire damage is classified as major damage when somebody dies or a ship is lost during the accident. A ‘minor damage’ means that at least one part of the ship is unable to perform its function.

Only 80 passenger ship fire accidents were found from the GISIS accident database which is a relatively small number of cases for statistical analysis. However, the space distribution of fire incidents can be obtained from the data. Fire incident frequency in a passenger ship cabin is evaluated from numerous accident databases. The cabin fire frequency is about 3.0×10^{-4} per ship year. The presented value does not contain all fires. Small fires are excluded partially because there is no data available. A small enquiry to passenger ships that sail at Finnish territorial waters reveals that ignition takes place on a ship cabin area ca. 0.2 times per year; that is, once in five years.

3.4.4 Cabin fire scenarios

Three fire scenarios are analysed: an arson scenario where a bed is ignited by a powerful fire source at night and the cabin door is left open, a cigarette on a bed scenario where a burning cigarette is placed on the bed and the cabin door is closed, and a litter basket fire below a rack with some overcoats. The design fire for each scenario is chosen so that the heat attack on structures is considerable. The results of interest are the heat flux to structures, spread of fire and smoke stimulus to smoke detector, the temperature evolution of critical structures, and the temperature of water mist nozzle.

The geometry of the cabin used in the simulations is shown in Figure 14.

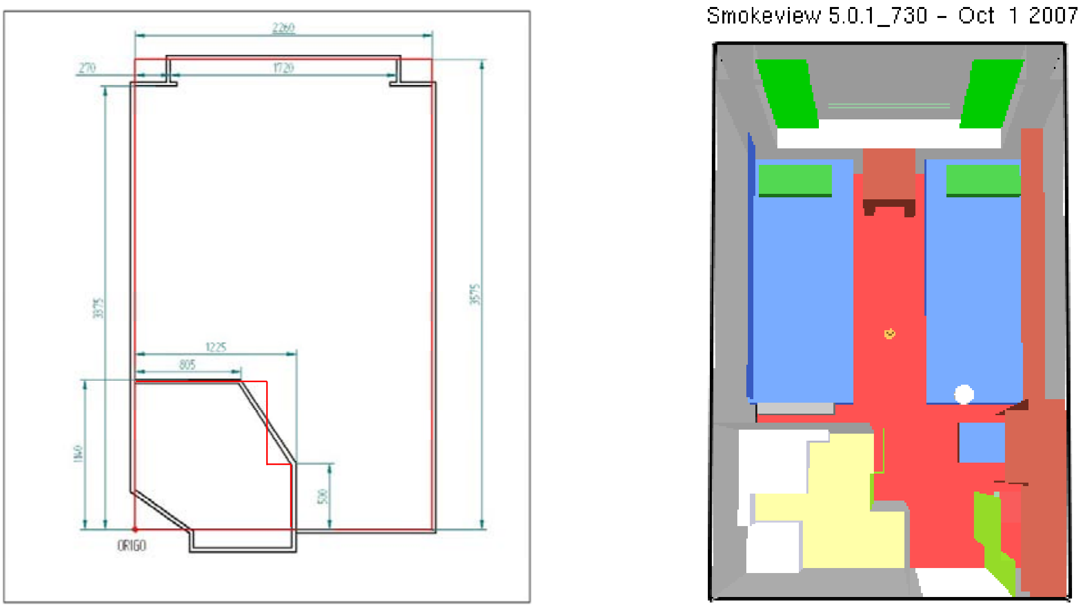


Figure 14. Picture of two-person cabin in a passenger ship used as an example.

The probability of the scenario is taken into account at risk evaluation. The scenario frequency is obtained from statistics, and the damage caused by each scenario is revealed by simulation. Fire risks are calculated combining the probability of the scenario and the damage distribution.

3.4.5 Input parameters

Finding single parameter values to describe the burning behaviour of cabin materials is not sufficient for quantitative fire risk analysis. Acceptable materials and products used in structures and furniture vary a lot. However, any material or product is not allowed to be used in shipbuilding. The materials used to build a passenger ship have to pass specific fire tests. Material parameters describing the burning of the materials used can be found from test results and literature. Also some other specific fire tests like the cone calorimeter (ISO 5660) or the room/corner test (ISO 9705) reveal the burning behaviour of materials. Numerous tests create a range of parameter space. If the frequency for a specific material to occur on a ship is found, then a parameter distribution can be formulated. For example, there are a limited number of accepted floor coverings to be used on the cabin floor. Each floor covering is tested at least according to the surface flammability test IMO FTP Code Part 5. In this test, peak heat release rate is measured in that test among other characteristics. The peak heat release rate varies from a floor covering to another, but those values together form a range of heat release rate peaks. If the distribution of used floor coverings is known, also the distribution of the peak heat release rate is known for floor covering materials.

Fire load is an amount of combustible matter that can act as a fuel to feed a fire. Fire load in a cabin consists of furniture, carpet, luggage, and the inner surface of ceiling and walls. The amount of fire load is presented as heat released per floor area. The fire load f in a cabin is calculated using equation

$$f = \frac{1}{A}\sum_{i=1}^{n} m_i q_i \, , \tag{3-19}$$

where m_i is a mass of material, q_i is its calorific value, and A is the cabin floor area. The actual fire load has some uncertainty because of the variation of luggage and other items in the cabin. There is some uncertainty in material parameters also. Because of the uncertainties, the fire load is calculated using a distribution of input values in addition to fixed values. The fire load distribution is calculated using 21 different types of cabins. Each cabin is calculated 1000 times varying input terms, see Figure 15.

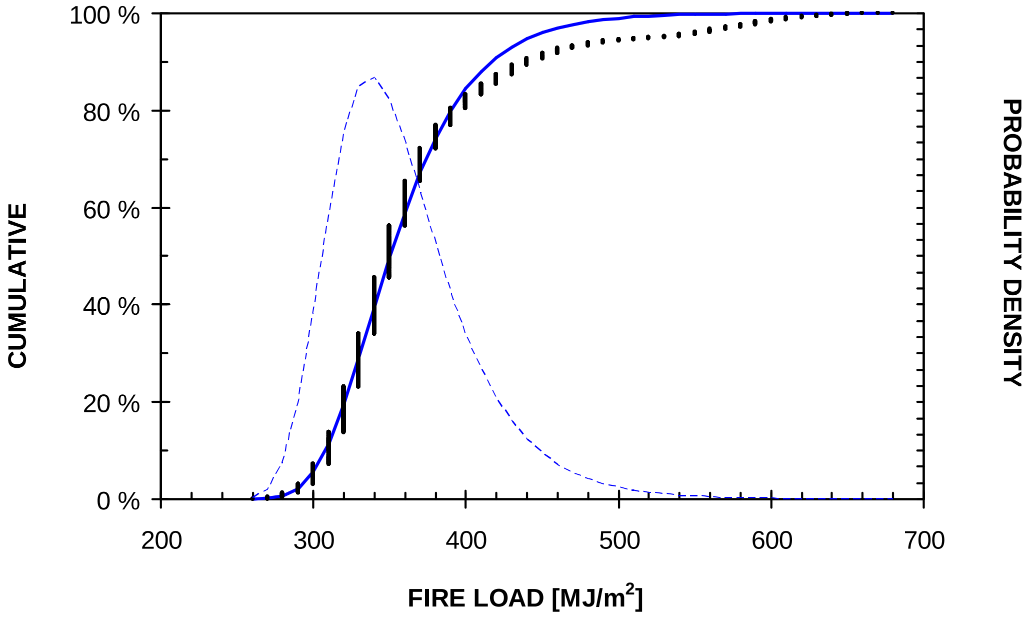


Figure 15. The fire load density distribution in a passenger ship cabin is calculated from 21 different cabin types. Each of them is calculated using 1000 different material and luggage settings.

Gumbel distribution F(x) defined in Equations (3-20) and (3-21) is fitted to the results. The Gumbel distribution is formed by using values a = 337.298 and b = 35.298.

$$F(x) = \exp\left(-\exp\left(-\frac{x-a}{b}\right)\right) \tag{3-20}$$

$$f(x) = \frac{\exp\left(-\frac{x-a}{b} - \exp\left(-\frac{x-a}{b}\right)\right)}{b} \tag{3-21}$$

The average value for the fire load in a passenger ship cabin is 358 MJ/m^2 and the 80 % fractile is 390 MJ/m^2.

The following random variables are used in cabin fire scenarios:

- initial fire growth rate
- burner HRR (initial fire)
- TV ignition temperature
- thickness of wall insulation
- temperature and volume of inflow and volume of suction
- fabric thickness on the bed
- fabric conductivity
- fabric heat capacity
- fabric heat of reaction
- fabric density
- padding thickness
- padding conductivity
- padding heat capacity
- padding heat of reaction
- time span from the alarm to the shut-down of air conditioning.

The output variables considered are the actuation times of the smoke alarm and water mist nozzle, heat release rate, the thermal impose on structures, and fire spread to the corridor.

3.4.6 Cabin fire simulation

Three different fire scenarios are examined. The selected scenarios are a deliberately ignited powerful fire on a bed, a small fire ignited by a cigarette on a bed, and a litter basket fire under a rack of overcoats. The Probabilistic Fire Simulation (PFS) tool is used to find the important input parameters that have an influence to heat release rate (HRR) development and the thermal stress at each scenario [42]. The heat release rate and growth rate of the initial fire make the biggest influence to the HRR development, maximum temperatures, and detector reaction times. The fabric in the bed has a smaller effect to HRR than the padding of the mattress. Fire retarded fabric resists the ignition against a small ignition source, but when the fabric is burnt away from one point of the mattress, the ability of the fabric to restrain the HRR growth is almost meaningless.

Supply air flow rate from a fan at the cabin ceiling has no effect on fire development, but correlation was found between the shutdown time of the air blower and the time when a water mist nozzle activates. The longer the blower works, the more time passes until the water mist is actuated.

The initial fire typically has a major effect on measured conditions in a closed space like a cabin. In the case of arson, possibilities to affect on the size of the initial fire are limited. In the case of a litter basket fire, however, minimizing the amount of packing material of goods sold on board has a meaningful positive outcome on fire load density in cabins. Other means to decrease fire load in a cabin is to limit the amount of luggage on board.

3.4.6.1 Branching probabilities for the time-dependent event tree

A passenger or a crew member can notice the fire. The probability of fire or smoke observation in an arson scenario depends on the deck watchman’s round frequency, the passenger load rate, the time of day, the state of fire, and the state of the cabin door (closed or open). The probability of human fire observation can be found combining all related subsets as described above.

A water mist nozzle activates as planned in 98 % of the cases. The water mist nozzle fails to operate at 2 % of the arson fire scenarios. The time when a nozzle actuates can be obtained from simulation results. The extinguishing probability is evaluated based on the actual nozzle test, and it depends only on the size of the fire.

The smoke alarm reliability is set to 99 %. The time when the stimulus from the fire is enough for an alarm is calculated directly from simulation results. The smoke alarm actuation probability for the event tree is therefore trivial.

The time from the point when a fire alarm is sounded to the moment when ship's fire fighting group can start to fight the fire is gamma distributed. The three-parametric gamma distribution is used to describe the quickness of the fire fighting group. The distribution used is

$$F(x) = \frac{1}{\Gamma(\alpha)} \int_0^{\frac{x-x_{\min}}{\beta}} y^{\alpha-1} e^{-y} dy = \frac{1}{\Gamma(\alpha)} \gamma(\alpha, \frac{x-x_{\min}}{\beta}) , \tag{3-22}$$

where the parameters are $\alpha = 2.06$, $\beta = 72.8$ and $x_{\min} = 240$ s. The average value is 6.5 minutes.

The probability for a successful extinguishing attempt is evaluated as follows. The success probability of the first-aid extinguishing is dependent on heat release rate. First-aid extinguishing is successful by the probability of 95 % when the heat release rate is between 0–100 kW, and the probability is null when the cabin is at the state of a fully developed fire. Intermediate values are linearly interpolated.

The effectiveness of water mist to extinguish the fire depends on the rate of heat release of the fire. The heat released from the fire has an effect on water evaporation volume. Droplet penetration through a jet flow to the seat of fire also depends on the heat release rate. A big fire evaporates the droplets and the cooling influence is effective, but an intense jet flow prevents the droplets to reach the seat of fire. An incipient fire releases only a small amount of heat. Water mist is ineffective when the evaporation volume is small, and an incipient fire needs a rather big local water flow to be extinguished. The threshold value for the extinguishing ability of water mist in a partially closed space is evaluated to be at heat release rate density of 2 kW/m^3 [43]. Water mist droplets do not evaporate effectively when the heat release rate density inside an envelope is lower than the threshold value. For example in a cabin of a volume of 17.5 m^3, the threshold value is 35 kW. On the other hand, a small fire needs only a small water flow to die out. When a water mist nozzle actuates in a space where the fire is fully developed and burning is oxygen limited, the fire dies out quite fast because the water evaporation lowers the temperature in the space, and the water mist displaces the remaining oxygen.

The branching probability where the water mist extinguishes the fire is 99 % at the time 0 s and at the time when the fire is oxygen limited. The lowest probability to extinguish the fire is 75 % when the heat release rate in the cabin is 35 kW. The intermediate values are linearly interpolated.

A fire fighting group can put the fire out only when they are at the site. Successful extinguishing by a fire fighting group is estimated to happen in 99 % of the cases.

If no action towards the extinction of the fire is carried out, the fire decays when the fire load has burned out. The time when the fire load has completely burned out is obtained from simulation.

All the presented branching probabilities describe roughly the system evolution probabilities. Some uncertainties are included in these values. The numerical value in the end can contain some inaccuracy but relative comparisons of different fire safety improvements can easily be achieved.

3.4.6.2 Time-dependent event tree

The state of the system is described in the time-dependent event tree presented in Figure 16 as follows:

A10: burning, not detected, water mist not activated
A9: fire load totally burned, not detected
A8: burning, the fire has been detected, water mist not activated
A7: burning, the fire has been detected, the fire fighting group is unsuccessful, water mist not activated
A6: burning, the fire has been detected, water mist activated but extinguishing failed, the fire fighting group not at the site
A5: burning, the fire has been detected, the fire fighting group and water mist unsuccessful
A4: fire load totally burned, the fire has been detected
A3: the fire fighting group successful
A2: water mist extinguished the fire
A1: first-aid extinguishing successful.

The fire is ignited at time t = 0 s. The system (cabin, corridor, fire, and fire safety systems) is at state A10: there is a fire but it has not yet been detected. The fire is detected by high probability during the next two time intervals. The system is then at state A8. Four minutes after the alarm also states A3 and A4 are possible when a fire fighting group can reach the fire scene. All system state changes are calculated using branching probabilities as explained in the previous section.

The time-dependent event tree method reveals weaknesses in fire safety and brings out possible development trends. The influence of single fire safety improvements is easy to check after the formation of the time-dependent event tree. The effects to damage risk can immediately be found by varying input parameters like water mist actuation temperature or the reliability of fire safety systems.

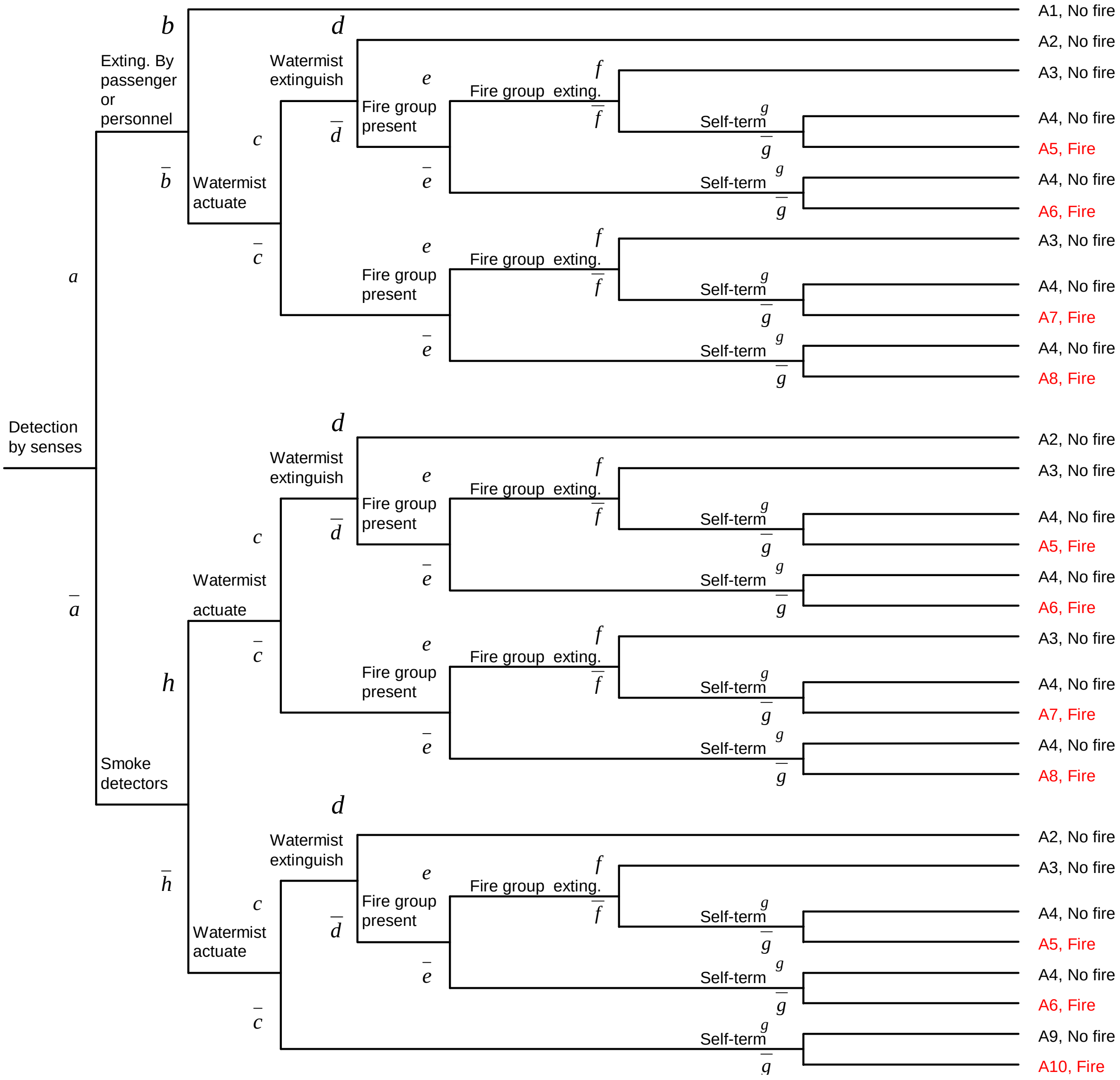


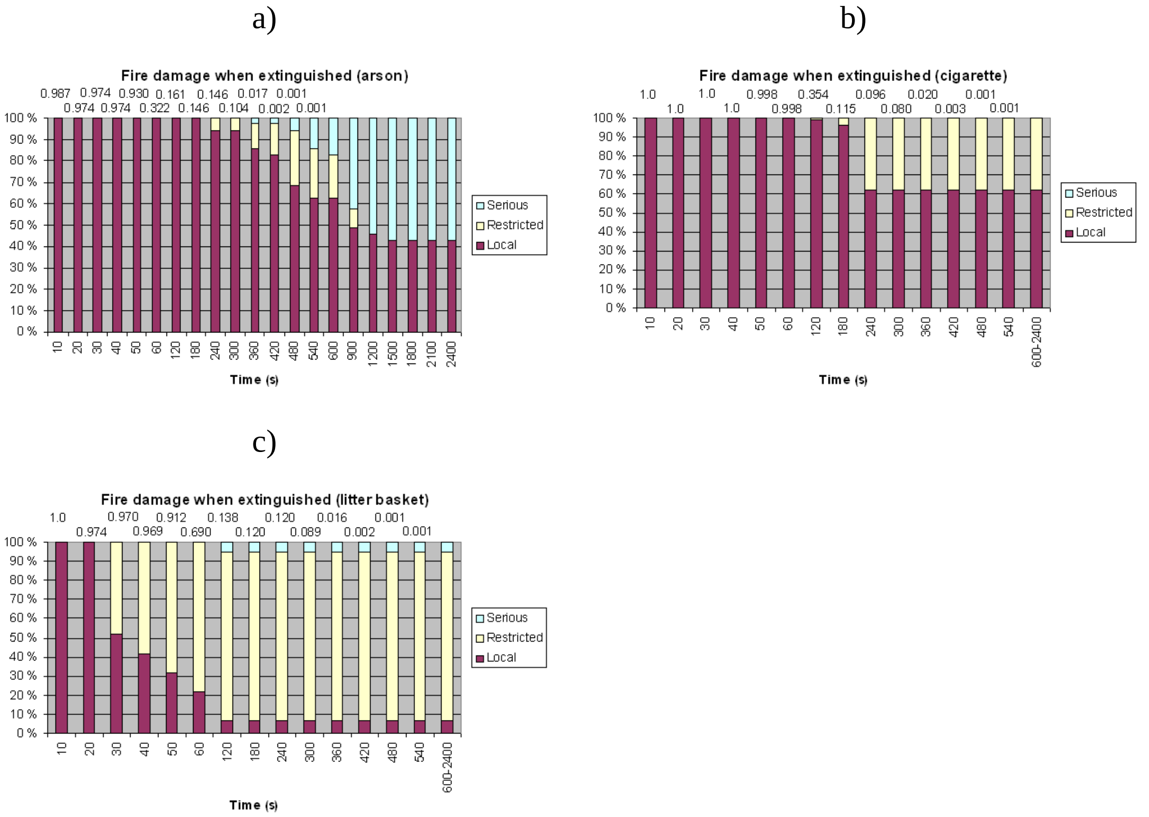
Figure 16. Time-dependent event tree of a cabin fire is constructed at every time interval. Branching probabilities (a–h) and complementary probabilities redirect the system.

3.4.6.3 Fire damage probability

The damage due to fire is divided to three categories. A local fire does not spread from the ignition point. All fires are at first in “local” state. A restricted fire spreads inside the cabin. All fires spreading from their ignition point to other objects but not yet out of the cabin are at “restricted” state. A “serious” fire has flashed over or spread to the corridor or to another cabin.

Fire simulation can be used to determine the fire damage. The time-dependent event tree shows the probabilities of the system states. The system state reveals the time when the fire has died out. This moment can be compared to fire simulation showing the probability of such fire damage.

The probabilities of different fire damage categories in each scenario at each time interval are shown in Figure 17. The fire damage at each time interval is the probability of the damage scenario if the fire has developed to that time interval. The total damage risk is obtained from the figure by summing up the presented probability values.


a)

b)

c)

Figure 17. Probabilities of fire damage categories. The time intervals are listed on the horizontal axis. The distribution of the three damage severity categories is on the vertical axis. Topmost is the probability of the fire in that scenario at that time interval.

3.4.7 Summary of cabin fire simulation results

A cabin fire on a passenger ship is ignited once every 5 years. The frequency for a cabin fire is therefore 0.2 per ship year. Most of the fires are caused by human actions. Cabin fires propagate beyond the cabin borders by a frequency of 3.0×10^{-4} 1/a. The decrease of the ignition frequency in cabins is very difficult to achieve. Some kind of passenger security check could help to reduce serious arson attempts. The ignition frequency could increase in the future because of bigger cruisers, but the amount of severe consequences can be diminished by emergency planning.

Fire safety objectives given to passenger ships can be met by using performance-based fire safety design. If the simulated fire induced damage is adequately small compared with the performance criterion, the solution can be approved. Fire development is resolved by using fire load entities and material parameter distributions obtained from different fire tests. A verified and validated fire simulation tool can be used to solve the fire development. To solve fire induced damage, the time-dependent event tree is used in connection with the fire simulation tool. Using this method, the effects of fire properties of materials on heat release rate and fire development can be determined. A time-dependent event tree can govern the dynamic character of the fire. Thus, successful extinguishing attempts and damages caused by the fire can be evaluated more accurately. The time-dependent event tree method is the only way to model extinguishing probabilities and other actions having an effect to the fire evolution at each time interval.

The initial fire growth rate and heat release rate have a major effect to fire evolution. Maximum heat release rate is achieved when the cabin door is left open. A straight route from the cabin to the corridor can lead to the flashover of the cabin. The flashover can happen in the arson scenario in 50 % of the cases if the door is open and nothing interrupts the evolution of fire. The probability of a flashover is only 0.08 % when active extinguishing methods are used.

The “cigarette in bed” scenario never caused a serious damage, even if fire fighting actions never took place. However, the damage caused by the fire could be reduced by fire fighting.

A cabin fire can spread through an open door to the corridor, or through a wall or a ceiling to the void space between the cabins and the hull. When a fire can develop freely in an open-door cabin, the temperature can momentarily reach higher levels than the temperature in a standard fire test. A fire tested cabin wall structure was evaluated against simulated temperature development curve. A cabin fire in flashover can spread through the wall and ceiling structure if there are combustible items on the non-burning side of the wall.

The arson scenario could cause serious damage (i.e. spread beyond cabin borders) by the probability of 1.7×10^{-4} per passenger ship year. It is comparable to the probability of all serious fire incidents obtained from accident statistics, 3.0×10^{-4}.

None of the simulated fires in a cabin with a closed door developed to a state where serious damage occurs. The simulation did not reveal cases where fire can spread through a wall or a ceiling. The model used cannot deal with temperature-induced deformation of the structure. The cabin walls and ceiling are built using thin steel plates. Stiffeners and frame structure are also made of steel. Steel plates deform at high temperatures which may cause a joint to open. The model used cannot predict when the joint is about to open or when the steel frame twists so that flames could pass to the other side of the wall. The temperature development to the wall or ceiling panel can be exported from simulations and analysed in more detail elsewhere.

3.4.7.1 Passive means for fire safety in passenger ship cabins

Class B-0 barrier does not stop the fire spreading from a cabin to void spaces in the case of an uncontrolled fire. All ducts and cables going through barriers should be mounted using incombustible materials. Corners, joints, bushings and recesses need special attention because the dynamic load from the fire is usually largest in those places. Voids between cabins should be always minimized. Installing an extinguishing system in voids with significant dimensions should be considered.

The cabin door should be of self-closing type. A door pump closes the door automatically when the door is released.

Decreasing fire load always helps to minimize the fire induced risks. An important means to reduce fire damages in a cabin is the careful selection furnishing materials. Bedding materials should be well insulating, and have low heat of combustion, high ignition temperature and high heat of reaction. Inherently flame resistant or fire retardant (FR) treated fabrics should be used in cabins. The FR treatment should preferably be implemented to the fabric during fibre making process, because FR agents applied as after-treatment can get washed away more easily.

The expectation value of fire damage is always reduced by reducing fire load. The fire load brought by a passenger to the cabin can be reduced by introducing a weight limit to passenger's luggage, or by diminishing wrapping materials of products sold on board. When the fire load in a cabin is 350 MJ/m^2, the duration of the maximum heat release rate phase of an uncontrolled fire is about 6–12 minutes. If the fire load in a cabin is diminished to 280 MJ/m^2, the maximum heat release rate phase lasts only 0–6 minutes. ´The decrease of fire load affects most to the temperatures measured at the unaffected side of the wall. The biggest single fire load entity in the cabin is the carpet on the floor. The low flame spread test ensures that the carpet is poorly ignitable and the flame spread on the carpet is limited. However, the carpet is significant as a fire load entity in the cabin.

3.4.7.2 Active means for fire safety in passenger ship cabins

The most effective position of a water mist nozzle is at the centre of the ceiling covering the beds. A nozzle above the door facing to the cabin prevents the fire from spreading to the corridor, but usually such a position leads to shadow areas which water mist cannot reach properly. The goal should always be to extinguish the fire as soon as possible. Therefore, it is justified to use a sensitive nozzle.

The smoke detector should be placed in the middle part of the ceiling but not beside an air conditioning blower. The blow of the air conditioning system may prevent the entrance of smoke to the detector.

3.5 Risk-based modelling of a cabin area of a multi-purpose icebreaker

The objective of the work was to model the planned cabin area of the multi-purpose icebreaker MSV Botnica and to develop risk-based analysis methods of the evacuation safety of cabin areas.

3.5.1 Description of the modelling object

The object of modelling is the planned cabin area on the third bridge deck of the multi-purpose icebreaker MSV Botnica. The design of MSV Botnica and the planned cabin area are shown in Figures 18 and 19, respectively.

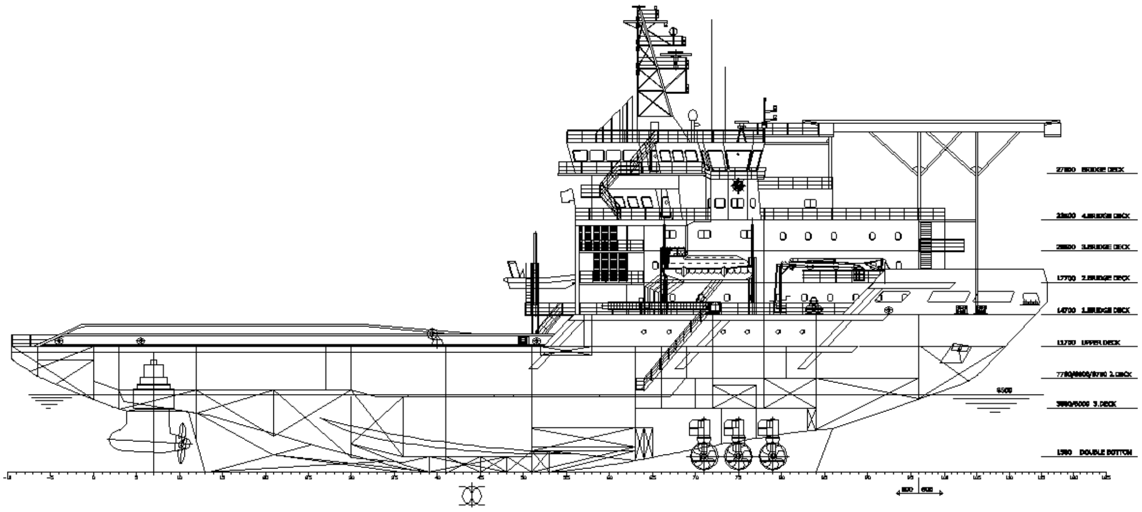


Figure 18. Multi-purpose icebreaker MSV Botnica.

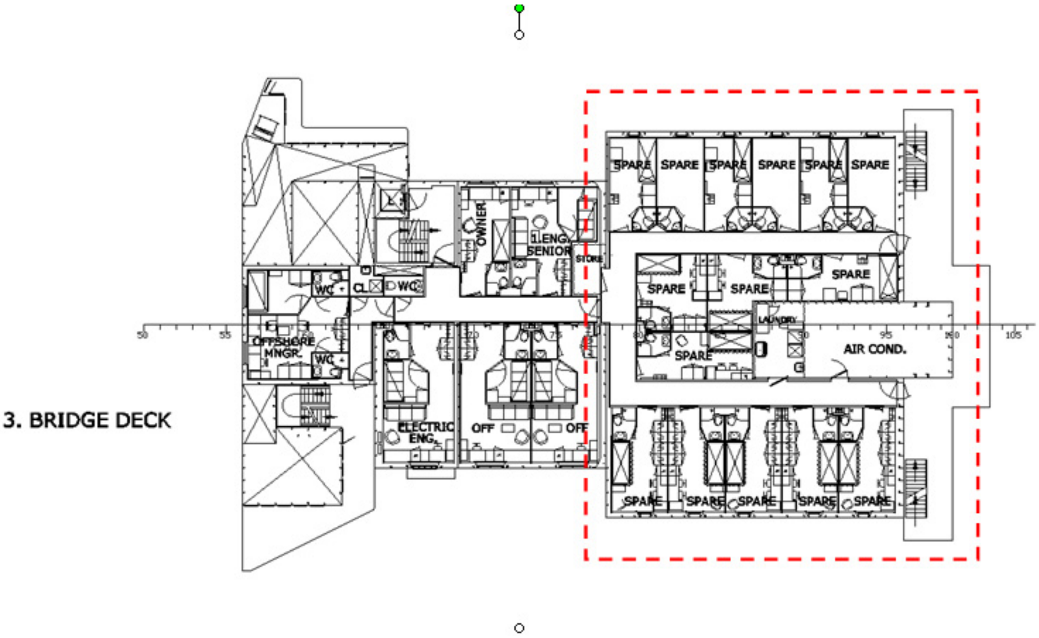


Figure 19. Planned cabin area on the third bridge deck of MSV Botnica.

3.5.2 Cabin area scenario

Evacuation from the cabin area on the third bridge deck is modelled in the case of a fire in a single cabin. The fire event is the design fire of a cabin defined by Karhula [28] in the case of arson. The spread of fire and smoke are simulated assuming that the door of the cabin in fire is open and the doors of other cabins are closed. The evacuation of the passengers is simulated simultaneously with the fire using the following assumptions:

- The passengers (1/cabin) are adults and situated randomly in the cabin area.
- The fire is detected by a smoke detector with the probability of 99 %. In the rest of the cases, the fire is detected by human senses.
- The response to fire is independent of the means of detection.
- The passengers move directly to the nearest door and are safe when exiting the fire compartment.

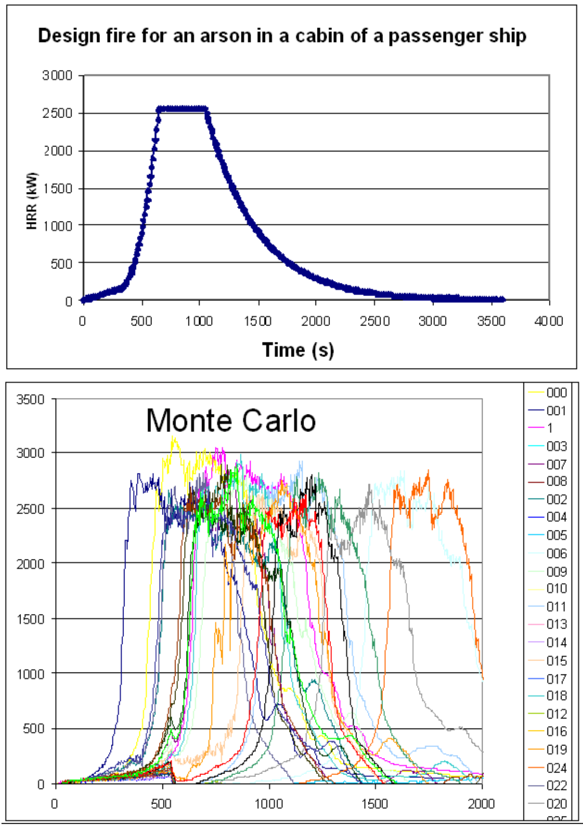
3.5.3 Analysis methods

The simulations were performed using the FDS program [23] which is a computational fluid dynamics (CFD) model of fire-driven fluid flow. FDS solves numerically a form of the Navier-Stokes equations appropriate for low-speed, thermally driven flow with an emphasis on heat and smoke transport from fires. The program includes an evacuation module, FDS+Evac [44], where each evacuee is described by its own equation of motion. FDS+Evac enables the simultaneous simulation of fire and evacuation, taking into account the effect of fire on egress and the exposure of people to smoke gases during the egress. The FDS+Evac model of the simulated area is presented in Figure 20. The model parameters are listed in Table 11. The heat release rate of the design fire for arson in a cabin of a passenger ship is shown in Figure 21.

Figure 20. FDS+Evac model of the cabin area.

Table 11. Modelling parameters.

Parameter	**Value**	**Method/Reference**
Heat release rate	Heat release rate of the design fire for arson in a cabin of a passenger ship (Figure 21)	Karhula [28]
Smoke yield	0.04 kg/kg	Weighted average of smoke yields of materials [28]
CO yield	0.02 kg/kg	Weighted average of CO yields of materials [28]
Dimensions and walking speed of passengers	FDS+Evac defaults	FDS+Evac manual [44]
Detection time: smoke detector Detection time: human senses	Triangular distribution (t_{peak}=17.9 s, t_{min}=17.4 s, t_{max}=19.1 s) Truncated normal distribution (t_{mean}=190 s, σ=40 s, t_{min}=5 s, t_{max}= 300 s)	Distributions defined on the basis of Karhula [28]
Reaction time	Weibull distribution (α=1.517, λ=0.019)	[45, 46]



$\dot{Q}(t)=0{,}5t$	$0\le t\le t_0$
$\dot{Q}(t)=\dot{Q}_0(\frac{t-t_0}{t_g})^2+0{,}5t_0$	$t_0<t\le t_1$
$\dot{Q}(t)=\dot{Q}_{\max}$	$t_1<t\le t_2$
$\dot{Q}(t)=\dot{Q}_{\max}\,e^{-(\frac{t-t_2}{\tau})}$	$t>t_2$
$t_0=310s, t_1=660s, t_2=1050s$ $\tau=440s, Q_{\max}=2550kW$	

Figure 21. Heat release rate of the design fire for arson in a cabin of a passenger ship.

If the situation is examined on the basis of Monte Carlo simulations of the cabin fire (Figure 22), a more detailed analysis of the simulation results is needed. The results of the Monte Carlo simulations can be divided to two groups based on the occurrence of a flashover during the first 9 minutes of the fire. Both groups can be parameterized separately, resulting in heat release rate curves describing flashover and non-flashover cabin fires (Equations (3-23) and (3-24), respectively). The distributions of the parameters Qmax, tg,1 and tg,2 are presented in Table 12. Heat release rate curves described by Equations (3-23) and (3-24) are shown in Figure 23. Using these heat release rate curves, the Monte Carlo simulation of the cabin area can be performed.

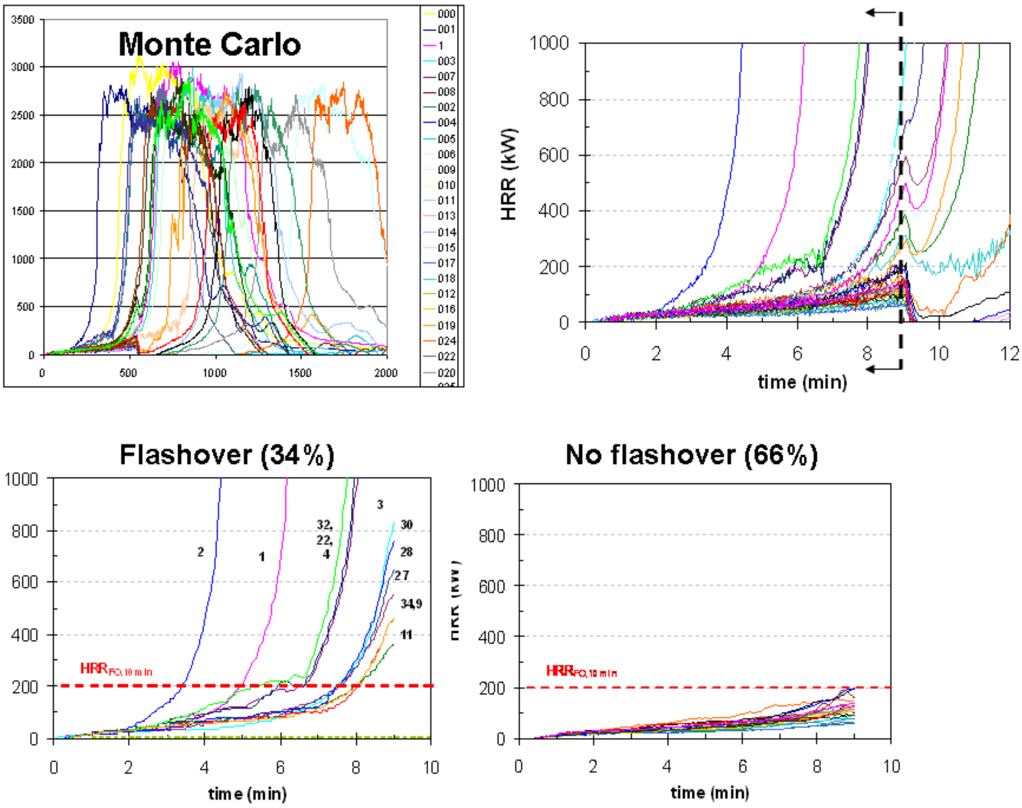


Figure 22. Analysis of Monte Carlo simulations of the cabin fire.

Flashover fires:

$$\dot{Q}(t) = \min\left\{1000 \cdot \left[\exp\left[\left(\frac{t}{t_{g,1}}\right)^{p_1} + \left(\frac{t}{t_{g,2}}\right)^{p_2}\right] - 1\right], \dot{Q}_{\max}\right\} \tag{3-23}$$

$p_1 = 1{,}25$

$p_2 = 8$

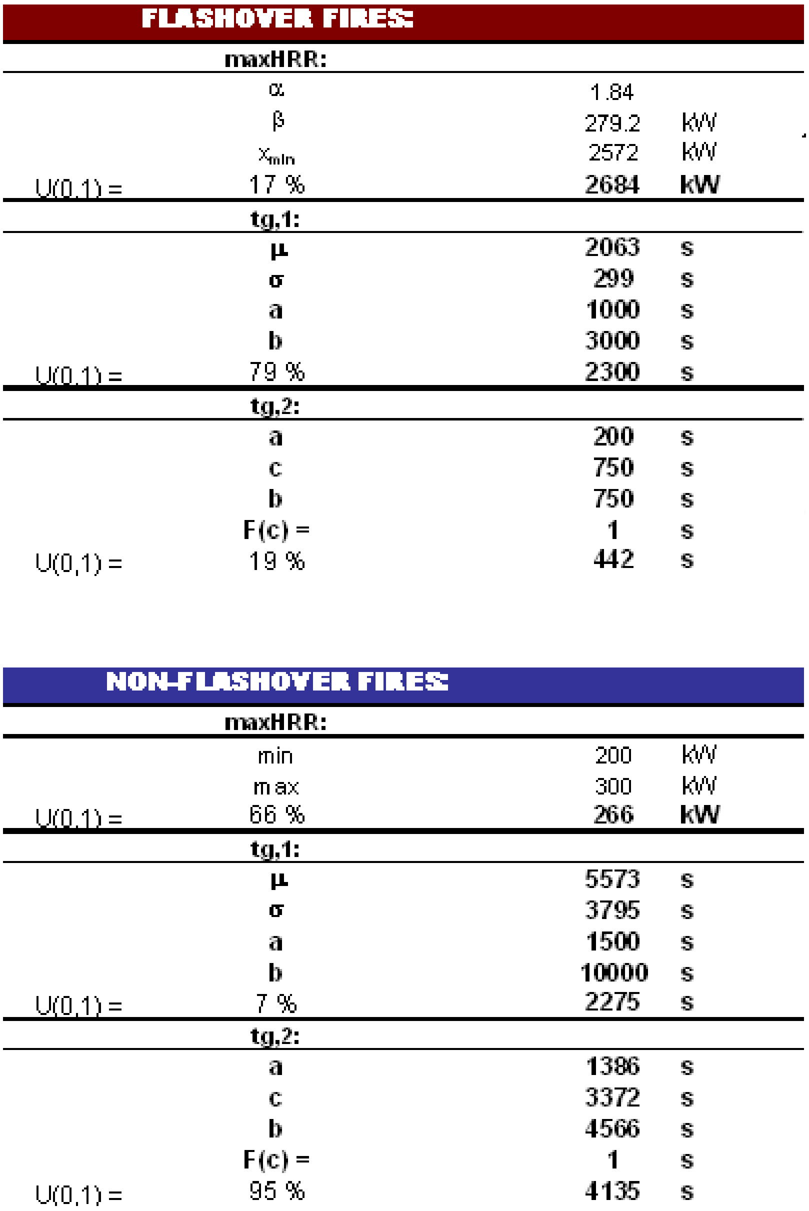
Non-flashover fires:

$$\dot{Q}(t) = 1000 \cdot \left[\left(\frac{t}{t_{g,1}}\right)^{p_1} + \left(\frac{t}{t_{g,2}}\right)^{p_2} \right] \tag{3-24}$$

$p_1 = 1$

$p_2 = 2$

Table 12. Distributions of heat release rate curve parameters of cabin fire.



	FLASHOVER FIRES:		
	maxHRR:		
	α	1.84	
	β	279.2	kW
	x_{min}	2572	kW
U(0,1) =	17 %	**2684**	**kW**
	tg,1:		
	μ	**2063**	**s**
	σ	**299**	**s**
	a	**1000**	**s**
	b	**3000**	**s**
U(0,1) =	79 %	**2300**	**s**
	tg,2:		
	a	**200**	**s**
	c	**750**	**s**
	b	**750**	**s**
	F(c) =	**1**	**s**
U(0,1) =	19 %	**442**	**s**

	NON-FLASHOVER FIRES:		
	maxHRR:		
	min	200	kW
	max	300	kW
U(0,1) =	66 %	**266**	**kW**
	tg,1:		
	μ	**5573**	**s**
	σ	**3795**	**s**
	a	**1500**	**s**
	b	**10000**	**s**
U(0,1) =	7 %	**2275**	**s**
	tg,2:		
	a	**1386**	**s**
	c	**3372**	**s**
	b	**4566**	**s**
	F(c) =	**1**	**s**
U(0,1) =	95 %	**4135**	**s**

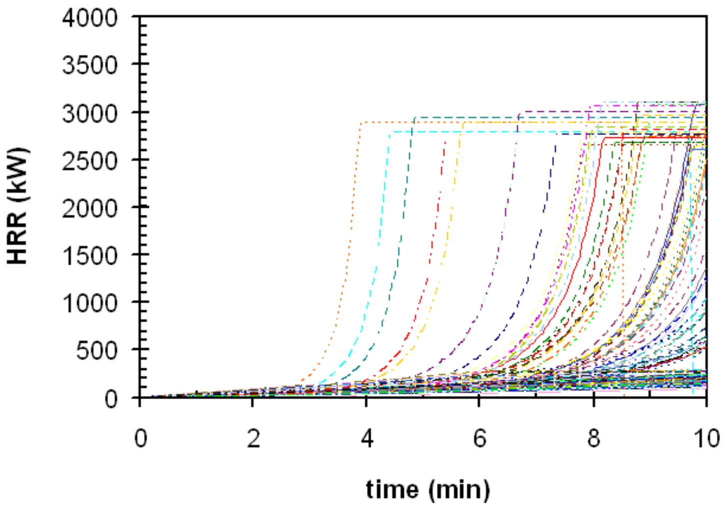
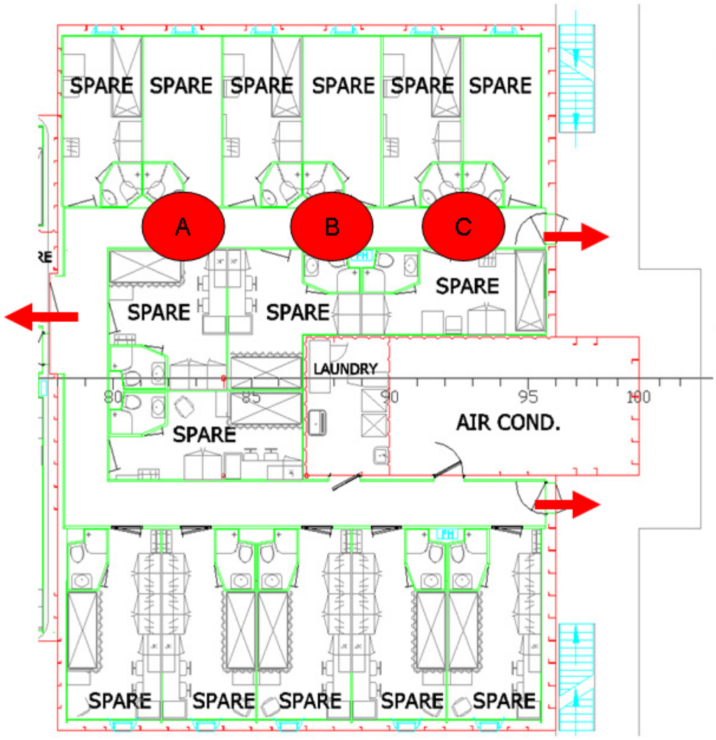


Figure 23. Heat release rate curves resulting from the parameterization of the cabin fire.

The location of the fire in the cabin area is random so that the ignition probability in all cabins is equal. On the basis of symmetry, the cabin area is divided to three zones, and probabilities for the location of fire in each zone are defined (Figure 24).



Fire	Location	Probability
A	Back	6/15
B	Middle	4/15
C	Front	5/15

Figure 24. Location of fire in the cabin area.

The following cases were selected for the simulations:

A: Cabin fire in the back part of the cabin area

a) the smoke detector is functional
b) the fire is detected by human senses.

B: Cabin fire in the middle part of the cabin area

a) the smoke detector is functional
b) the fire is detected by human senses.

C: Cabin fire in the front part of the cabin area

a) the smoke detector is functional
b) the fire is detected by human senses.

Since several parameters were selected from random distributions, ten realizations for each case were calculated.

Measurement points for the following quantities were set in corridors at the height of 1.6 m (Figure 25):

- temperature
- extinction coefficient
- CO concentration
- FED (Fractional Effective Dose).

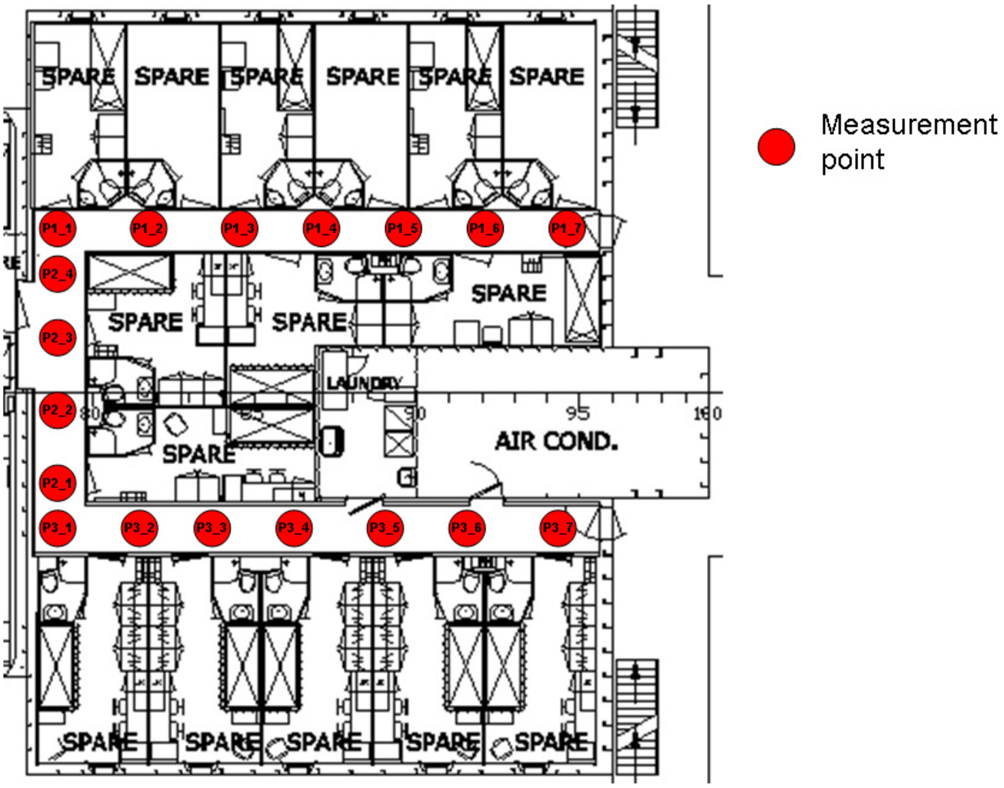


Figure 25. Location of measurement points in simulations.

The extinction coefficient describes the degradation of visibility as follows:

$$S = C / K_s \tag{3-25}$$

where

S = visibility (m)
K_s = extinction coefficient (1/m)
C = a constant depending on the object; for example, for a light emitting signboard C = 8 and for a light reflecting signboard C = 3.

Smoke slows down the walking speed due to reduced visibility and irritating and suffocating effects. In the FDS+Evac model, the reduction of speed is taken into account according to Equation (3-26):

$$v_i^0(K_s) = Max\left\{ v_{i,\min}^0, \frac{v_i^0}{\alpha}\left(\alpha + \beta K_s\right) \right\} \tag{3-26}$$

where

α = 0.706 (m/s)
β = -0.057 m^2/s
$v_{i\ ,\min}^0 = 0.1 \times v_i^0$
v_i^0 = initial walking speed.

The FED value (Fractional Effective Dose) describes the incapacitating dose due to the increase of CO_2 and CO concentrations and the decrease of O_2 concentration. In FDS, the FED value is calculated as follows:

$$FED_{tot} = FED_{CO} \times HV_{CO_2} + FED_{O_2} \tag{3-27}$$

where

$$FED_{CO} = 4.607 \cdot 10^{-7} (C_{CO})^{1.036} t \tag{3-28}$$

$$HV_{CO_2} = \frac{\exp(0.1930\, C_{CO_2} + 2.0004)}{7.1} \tag{3-29}$$

$$FED_{O_2} = \frac{t}{60 \exp[8.13 - 0.54(20.9 - C_{O_2})]} \tag{3-30}$$

where

t = time (s)
C_{CO} = CO concentration (ppm)
C_{CO2} = CO_2 concentration (%)
C_{O2} = O_2 concentration (% by volume).

3.5.4 Summary of cabin area results

3.5.4.1 Simulations with the design fire

When only the evacuation from the cabin area without the effect of heat or smoke is considered, the results of the evacuation simulations are as shown in Figure 26. If the fire is detected by a smoke detector, the egress of all passengers from the cabin area takes ca. 100–200 seconds. If the fire is detected by human senses, the time for complete egress is ca. 300–400 seconds. It can be concluded that simulations of 400–500 seconds after the ignition are sufficient for evaluating the evacuation safety.

If only the temperature development in the cabin area during the first 400 seconds is considered (Figure 27), a cabin fire in the front part of the cabin area is the most challenging case. The temperature reaches 200 °C in front of the fire cabin at the height of 1.6 metres in 400 seconds.

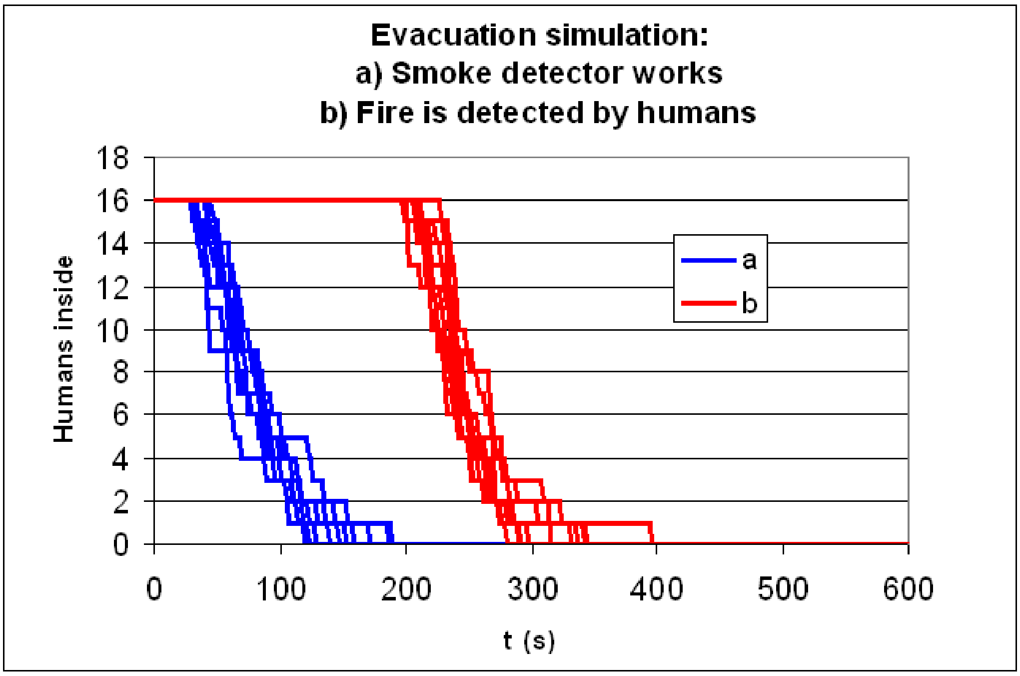


Figure 26. Evacuation without the effects of fire. Ten realizations of both cases were simulated.

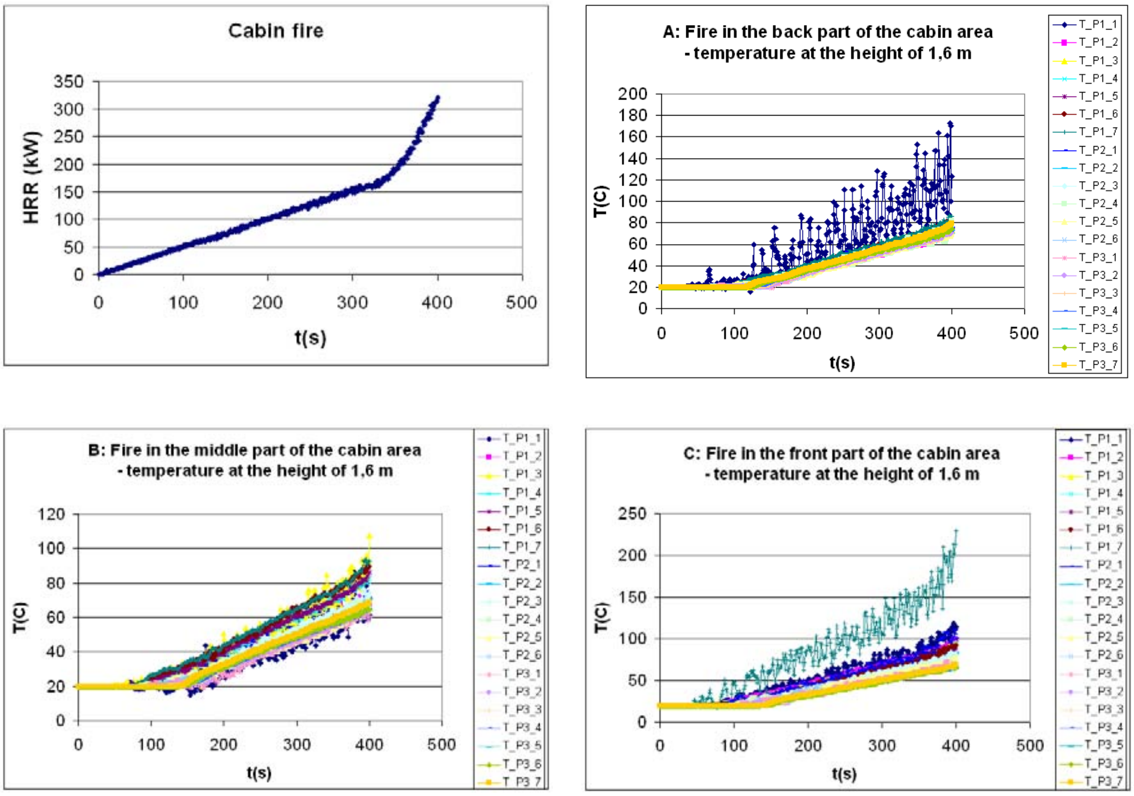


Figure 27. Heat release rate of the cabin fire and temperature development in the cabin area.

The results of simultaneous simulations of fire and evacuation for a cabin fire in the front part of the cabin area are shown in Figures 28 and 29. Figure 28 shows that the visibility decreases considerably in the early phase. In terms of CO concentration and FED value, evacuation is safe during 400 seconds, but after that the conditions deteriorate quickly. Figure 29 shows that evacuation is completed within 350 seconds. Therefore, no intoxicating exposure of evacuees takes place.

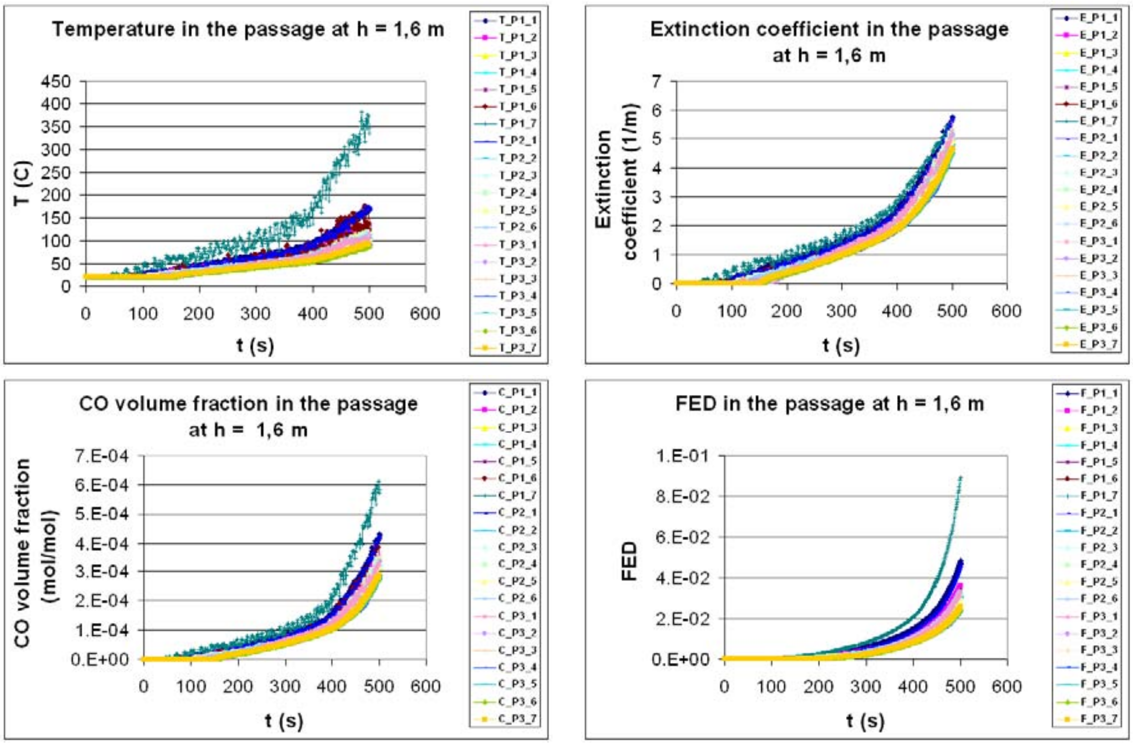


Figure 28. Results of fire simulations when the fire starts in the front part of the cabin area.

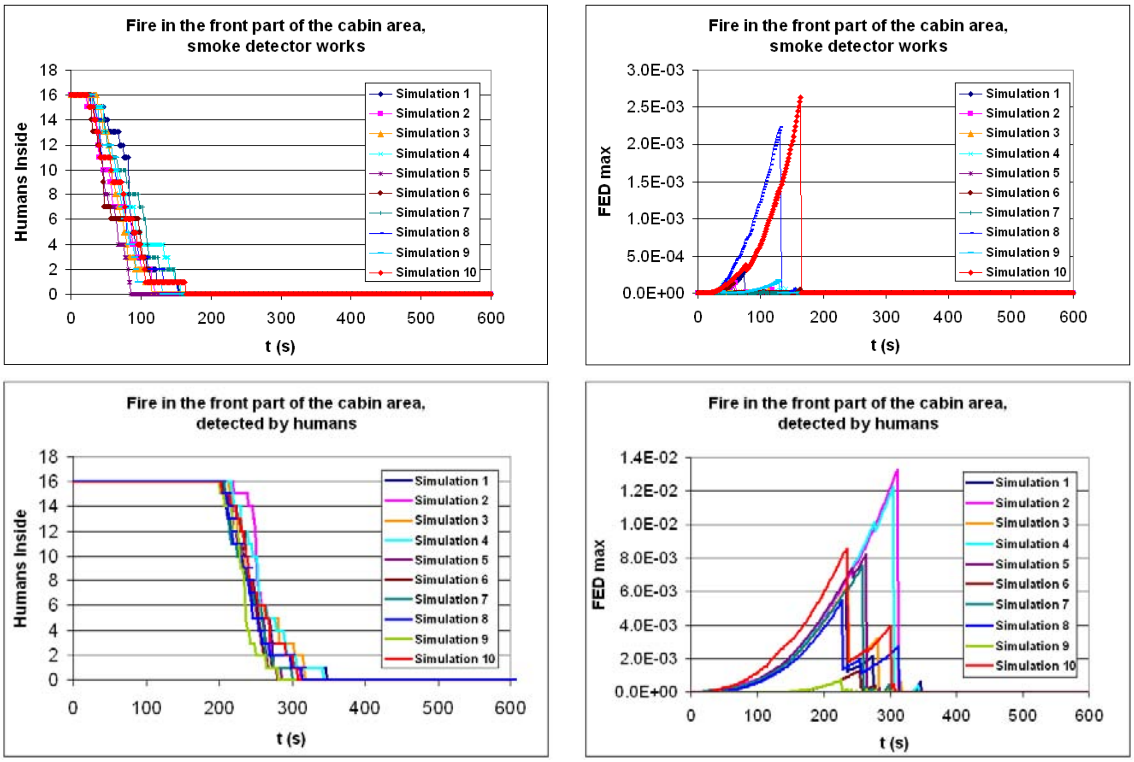


Figure 29. Results of evacuation simulations when the fire starts in the front part of the cabin area. Ten realizations were simulated.

3.5.4.2 Monte Carlo simulations

Monte Carlo simulations of the cabin fire [28] were made by varying the amount and quality of the fire load in the cabin, the material parameters, air conditioning during the fire, and environmental variables such as the amount of wall insulation and the quickness of automated safety procedures after fire detection. The results were a set of heat release rate curves of the cabin fire. In the Monte Carlo simulations of the cabin area, the following quantities were varied:

- location of the fire
- heat release rate of the fire
- detection time of the fire
- reaction times of the passengers
- size and walking speed of the passengers.

The purpose of the Monte Carlo simulations was to determine the F-N curves that describe the risk of the passengers in the evacuation situation during a fire in the cabin area. F-N curves show the dependence of the frequency of incidents on the number of threatened persons. In the simulations, the risk was assumed to be caused by decreased visibility and increased temperature at the evacuation routes.

First, the distribution of the realization time of a threat was determined. The threat was specified to be one of the following:

- temperature is more than 60 °C near an evacuation exit
- visibility of a light-reflecting sign is less than 3 m near an evacuation exit.

The results of the Monte Carlo simulations are shown in Figure 30. The distribution of the realization time of a threat in the cabin area can be described by a Gamma distribution with parameters $\alpha = 4.2$, $\beta = 0.96$ and $x_{min} = 4.5$ min.

Likewise, the time for a certain amount of people still being inside the cabin area during the evacuation situation was determined. For example, the time for $N = 2$ people still being inside the cabin area in the case where the smoke detector does not work (the fire is detected by human senses) can be described by Gamma distribution with parameters $\alpha = 15$, $\beta = 0.085$ and $x_{min} = 3.6$ min as can be seen in Figure 31. The Gamma distribution parameters for all values of N are determined the same way.

The frequency of the incident that for example two people are threatened can be calculated as the proportion of fires where $t_{threat} < t_{N=2}$ (Figure 32). By Monte Carlo integration the frequency per fire can be calculated for all values of N. As a result, we get F-N curves (Figure 33) that tell us how often (per fire) a certain number of people is threatened because of a fire in the cabin area. In this case, we calculated F-N curves separately for the cases of the smoke detector to work or not to work. These values can be compared with the acceptance criteria given in section 3.4.2 taking into account the probabilities of fires in accommodation areas.

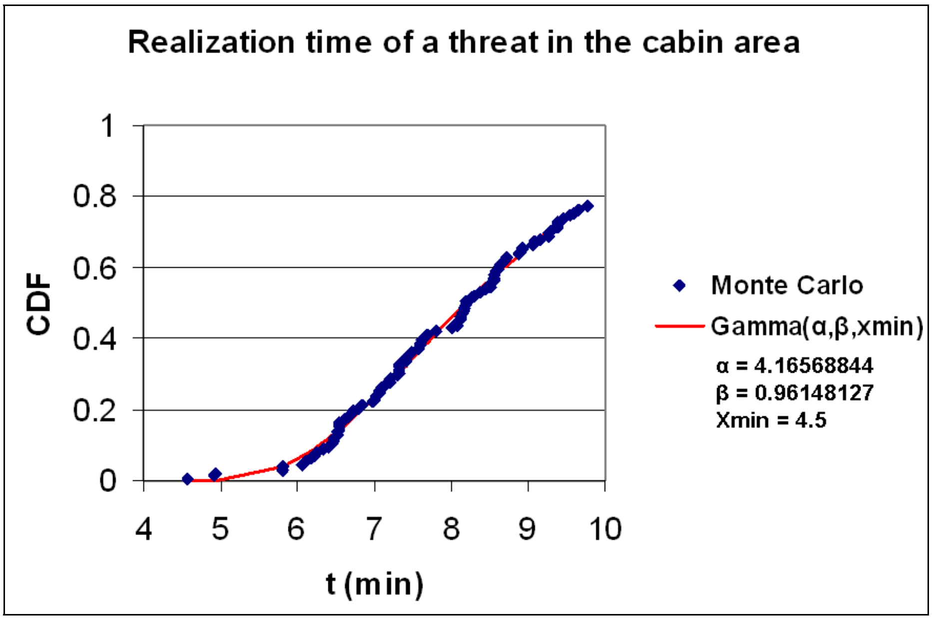


Figure 30. Distribution of the realization time of a threat in the cabin area (CDF = cumulative density function).

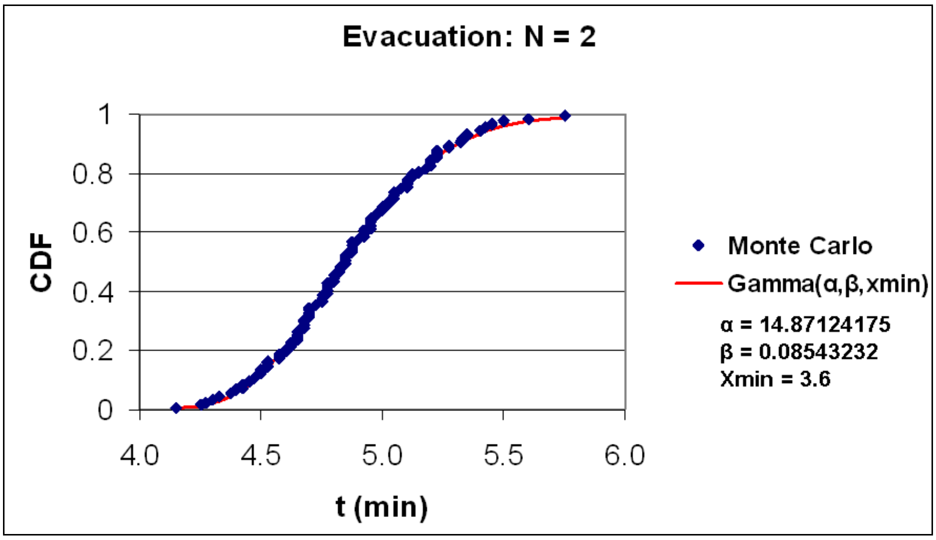


Figure 31. Distribution of N = 2 people still being in the cabin area in the case of the fire being detected by human senses (CDF = cumulative density function).

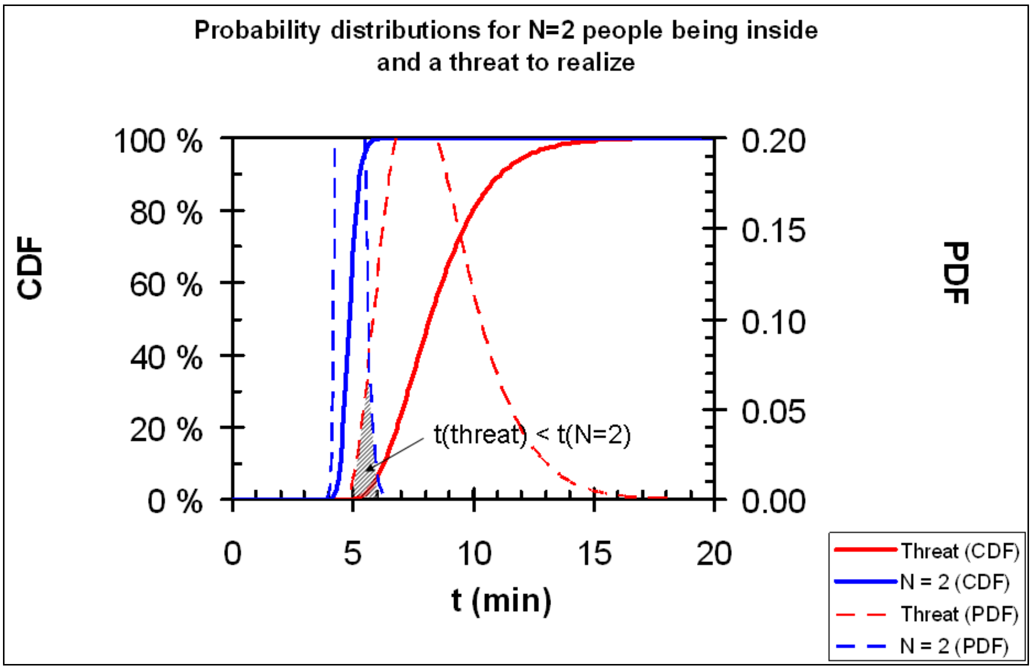


Figure 32. Probability distributions for N = 2 people being inside and a threat to realize (CDF = cumulative density function, PDF = probability density function).

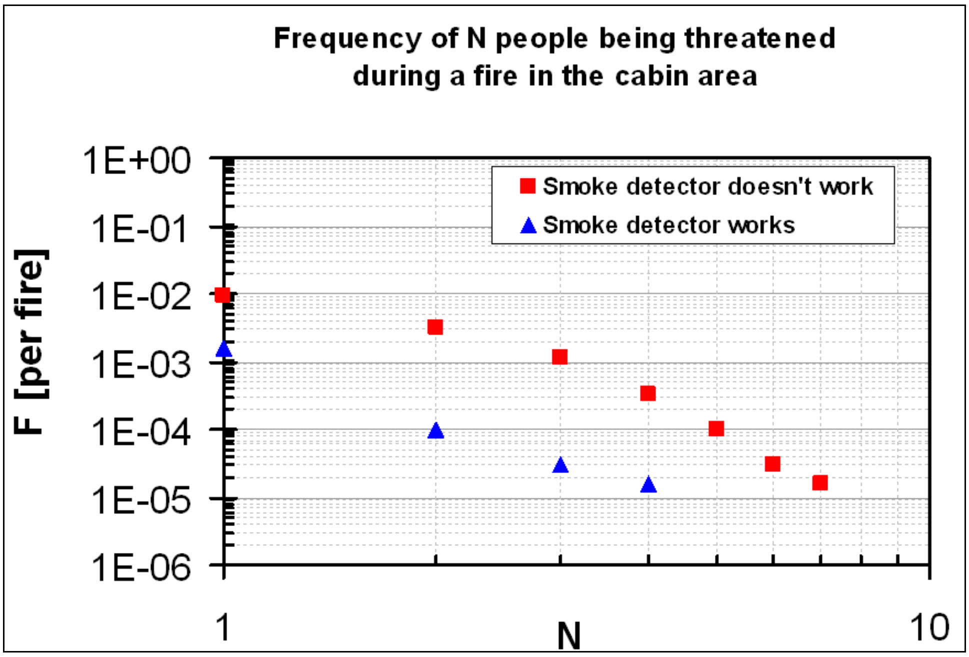


Figure 33. Frequency of N people being threatened during a fire in the cabin area.

3.6 Design fire heat release rates for shops on board

In this section, the methodology for using a fire simulation program to predict heat release rate is applied to shops on board.

On cruisers, there are typically at least one largish shop space (e.g. a tax-free shop) and several smaller boutique-type shops.

Direct assessment of the heat release rate of the combustibles on the basis of experimental data in such facilities as shops on board involves some difficulties:

- The fires can be very large, of the order of tens of megawatts, and the amount of experimental data with so high HRR values is limited but fortunately not entirely non-existent.
- The combustibles are not very well defined because
    - the stored items vary
    - the lay-out and storing height vary.

To overcome these problems, a methodology enabled by the version 5 of the FDS fire simulation program can be used to get an estimate of the heat release rate. The results show that – given the inherent uncertainties involved in our knowledge of the stored goods and their configuration – the accuracy of the HRR predictions obtained by using the methodology is sufficient for FSE usage.

3.6.1 Fire experiment data relevant to shops

3.6.1.1 Data from small or medium scale experiments

Figure 34 shows data on the heat release rate of single coats, and Figure 35 data on a rack of coats. Summary of the analysis of the data is shown in Figure 36.

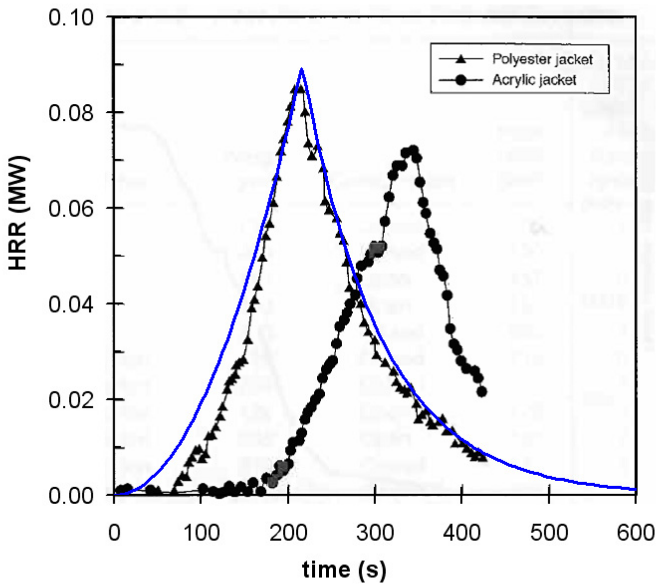
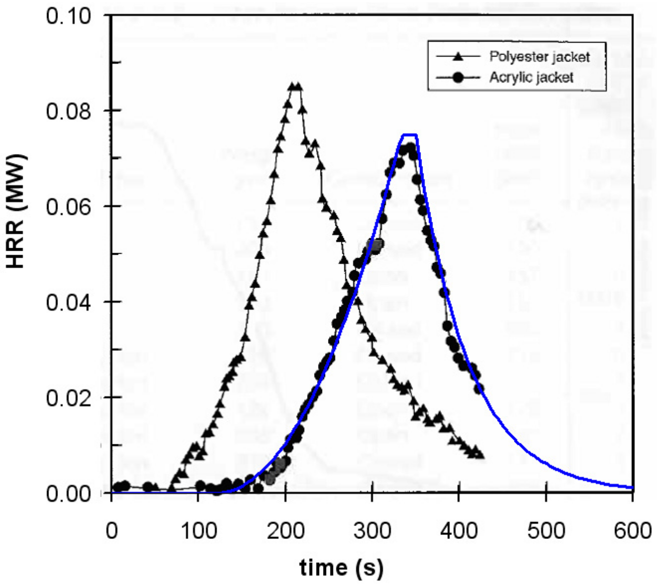
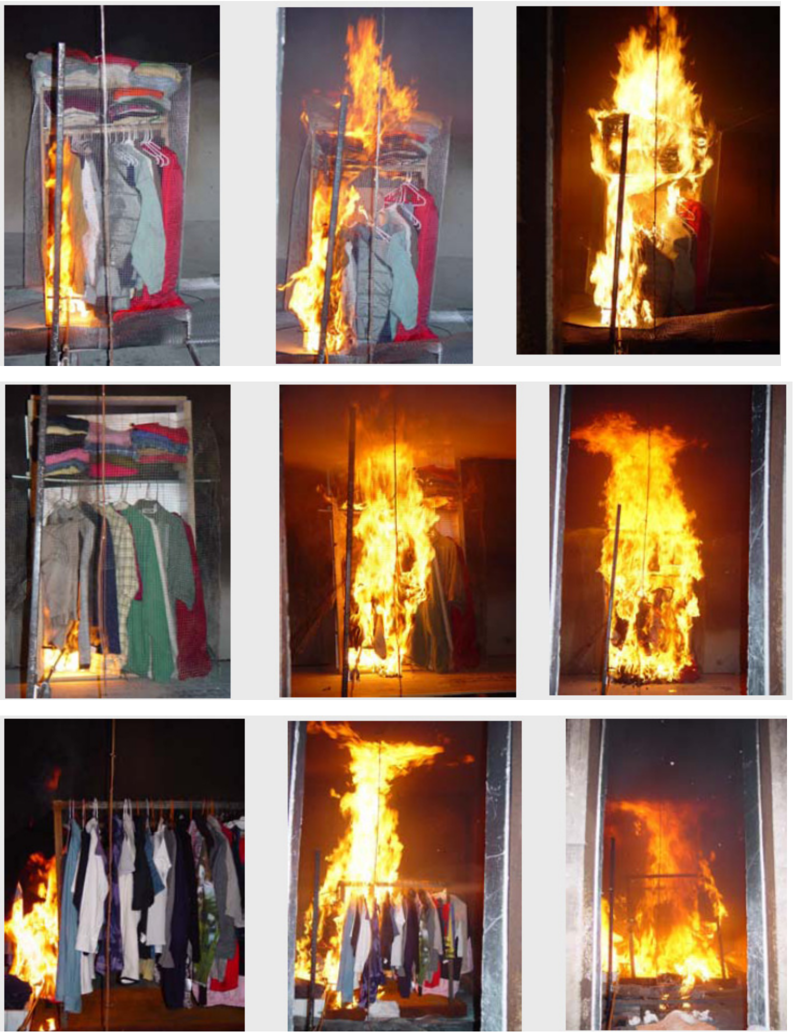
Polyester coat  	- shape: t^p - $p = 2$ - $t_g = 720$ s - $\dot{Q}_{max} = 90$ kW - $t_1 = 216$ s - t_2 not applicable - $\tau = 90$ s - $Q_{tot} = 14.6$ MJ - $D_{eff} = 0.68$ m (estimate) - $A_{floor} = 0.36$ m^2 (estimate) - $\dot{Q}''_{max} = 250$ kW/m^2 - $q'' = 41$ MJ/m^2
Acrylic coat  	- shape: t^p - $p = 2$ - $t_g = 780$ s - $\dot{Q}_{max} = 75$ kW - $t_1 = 214$ s - $t_2 = 230$ s - $\tau = 300$ s - $Q_{tot} = 11.1$ MJ - $D_{eff} = 0.68$ m (estimate) - $A_{floor} = 0.36$ m^2 (estimate) - $\dot{Q}''_{max} = 208$ kW/m^2 - $q'' = 31$ MJ/m^2

Figure 34. Data on burning of single coats [7].

Test setup and fire development: tests 3A, 3B and 3C



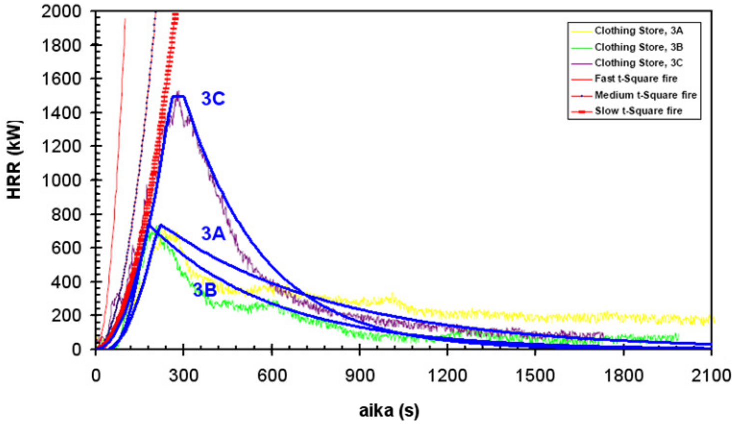
Test 3A

- $p = 2$
- $t_g = 210$ s
- $\dot{Q}_{max} = 750$ kW
- $t_1 = 182$ s
- t_2 not applicable
- $\tau = 600$ s
- $Q_{tot} = 500$ MJ
- $D_{eff} = 2.3$ m (estimate)
- $A_{floor} = 4$ m^2 (estimate)
- $\dot{Q}''_{max} = 190$ kW/m^2
- $q'' = 125$ MJ/m^2

Test 3B

- $p = 2$
- $t_g = 150$ s
- $\dot{Q}_{max} = 750$ kW
- $t_1 = 130$ s
- t_2 not applicable
- $\tau = 420$ s
- $Q_{tot} = 350$ MJ
- $D_{eff} = 2.3$ m (estimate)
- $A_{floor} = 4$ m^2 (estimate)
- $\dot{Q}''_{max} = 188$ kW/m^2
- $q'' = 90$ MJ/m^2

Time development of the fire



Test 3C

- $p = 2$
- $t_g = 210$ s
- $\dot{Q}_{max} = 1500$ kW
- $t_1 = 257$ s
- $t_2 = 300$ s
- $\tau = 270$ s
- $Q_{tot} = 605$ MJ
- $D_{eff} = 2.3$ m (estimate)
- $A_{floor} = 4$ m^2 (estimate)
- $\dot{Q}''_{max} = 750$ kW/m^2
- $q'' = 300$ MJ/m^2

Figure 35. Data on burning of coat racks [47].

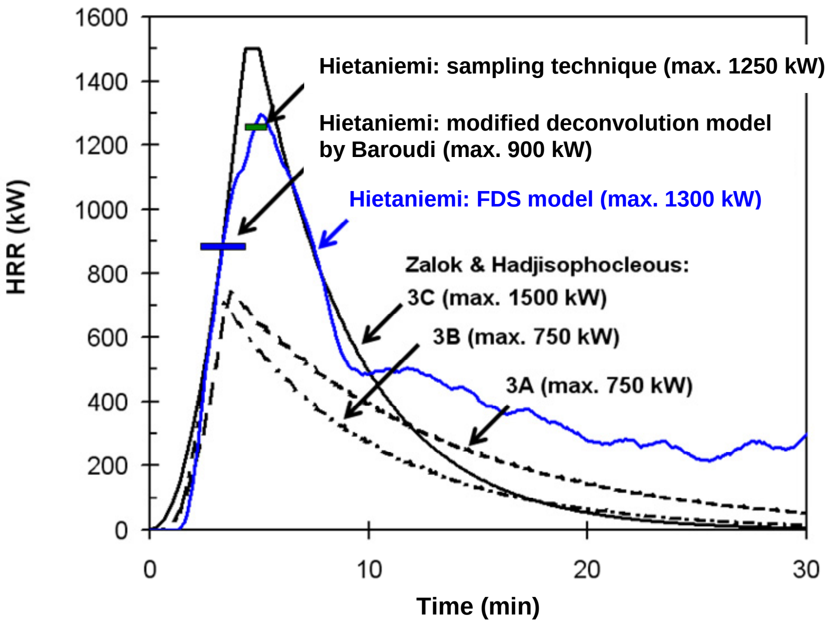


Figure 36. Experimental results and modelling of burning of ca. 10–15 coats.

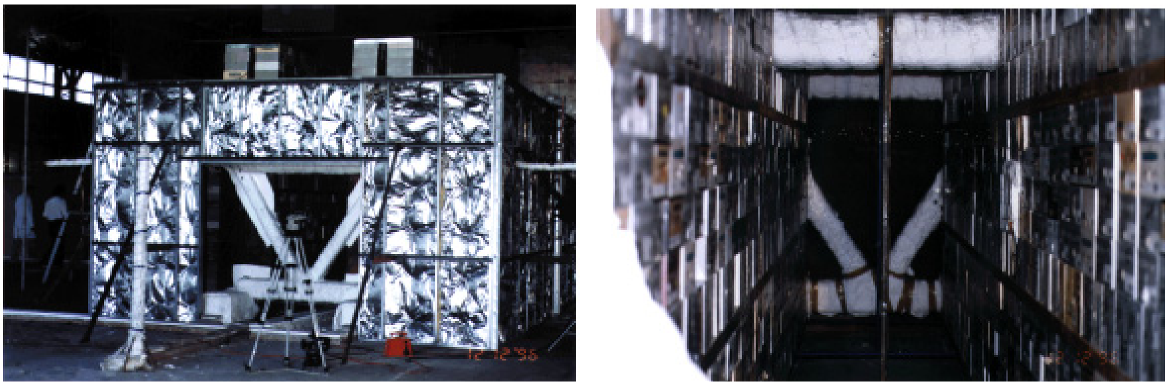
3.6.1.2 Specialty shops

In the 1990's Bennetts et al. [48] carried out a series of large-scale fire experiments to characterise fire hazards of shopping centres. Below we present the HRR data obtained in non-sprinklered experiments and demonstrate the influence of sprinkler systems by the empirical correlations given in section 3.2.6.1.

Cases where automatic suppression systems fails

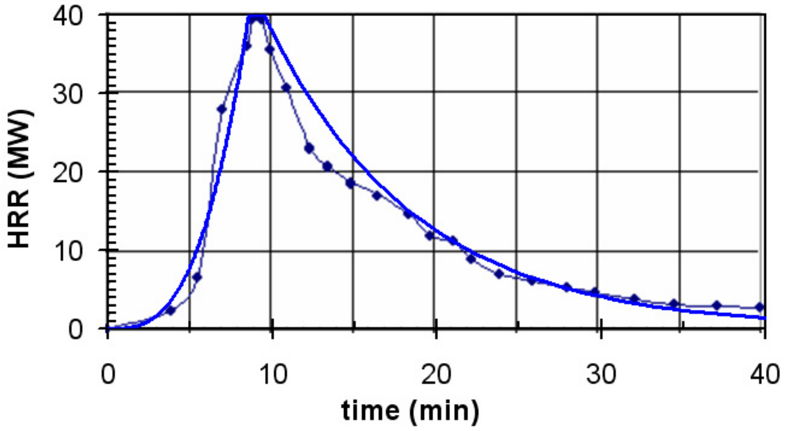
In non-sprinklered cases, the fires were very big, reaching up to 40-50 MW. They are shown below as follows:

- heat release rate of a flash-over fire in a shoe storage room (set-up: TEST SET-UP **– SHOE STORAGE.** Figure 37, HRR: Figure 38)
- heat release rate of a flash-over fire in a specialty shop (Figure 39).



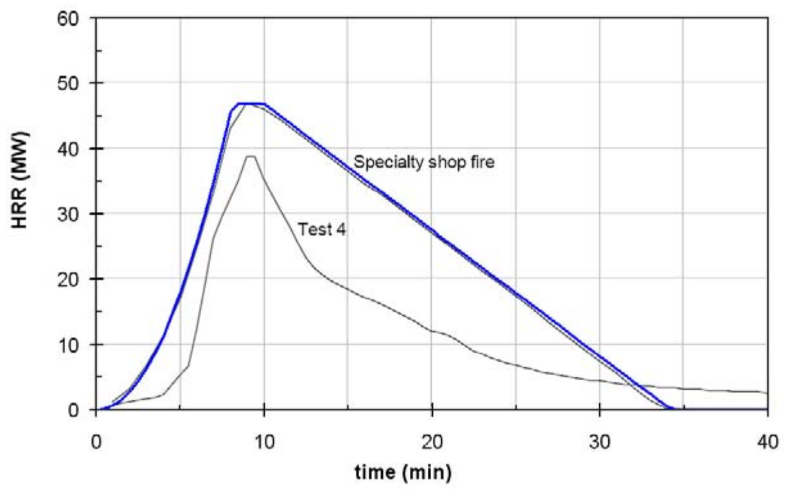
TEST SET-UP – SHOE STORAGE

Figure 37. Set up of the shoe storage fire experiment [48]: space height is ca. 3 m and opening size ca. 2 m × 2 m.



- shape: t^p
- $p = 3$
- $t_g = 150$ s
- $\dot{Q}_{max} = 40\ 000$ kW
- $t_1 = 513$ s
- $t_2 = 570$ s
- $\tau = 540$ s
- $Q_{tot} = 28\ 200$ MJ
- $D_{eff} = 4.5$ m (estimate)
- $A_b = 16$ m^2 (estimate)
- $\dot{Q}''_{max} = 2500$ kW/m^2
- $q'' = 1760$ MJ/m^2

Figure 38. Heat release rate of flash-over fire in a shoe storage room [48].

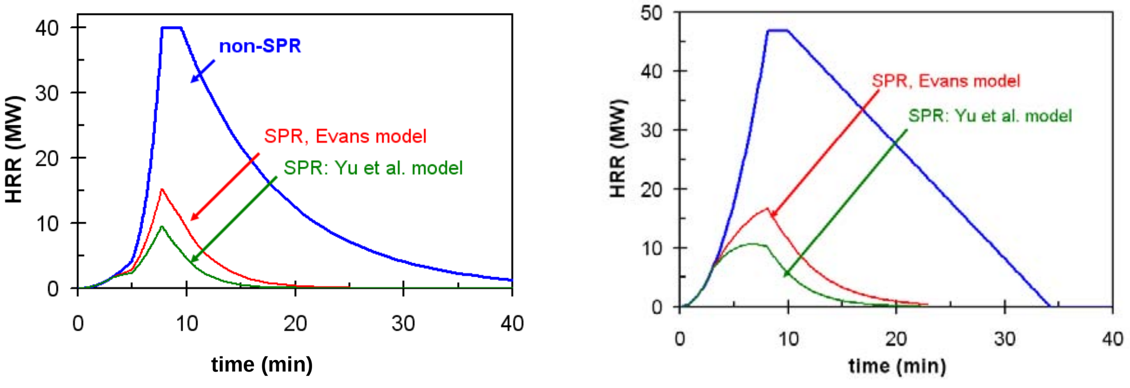


- shape: t^p, linear decay
- $p = 2$
- $t_g = 71$ s,
- $\dot{Q}_{max} = 47\,000$ kW
- $t_1 = 487$ s
- $t_2 = 595$ s
- $t_3 = 2055$ s
- $Q_{tot} = 47\,000$ MJ
- $D_{eff} = 4{,}5$ m (estimate)
- $A_b = 16$ m^2 (estimate)
- $\dot{Q}''_{max} = 2900$ kW/m^2
- $q'' = 2900$ MJ/m^2

Figure 39. Heat release rate of a flash-over fire in a specialty shop [48].

Cases where automatic suppression systems operate

The reliability and efficiency of suppression systems should be so high that fires as depicted above should be ignorable. Examples of the influence of automatic water suppression on the development of fire are presented in Figure 40.


a)

b)

Figure 40. Example of the influence of automatic water suppression on a) the shoe storage fire and b) the specialty shop fire. The height of the space is assumed to be 3 m and the activation time of the suppression system 3 min.

3.6.2 Example of modelling of HRR development

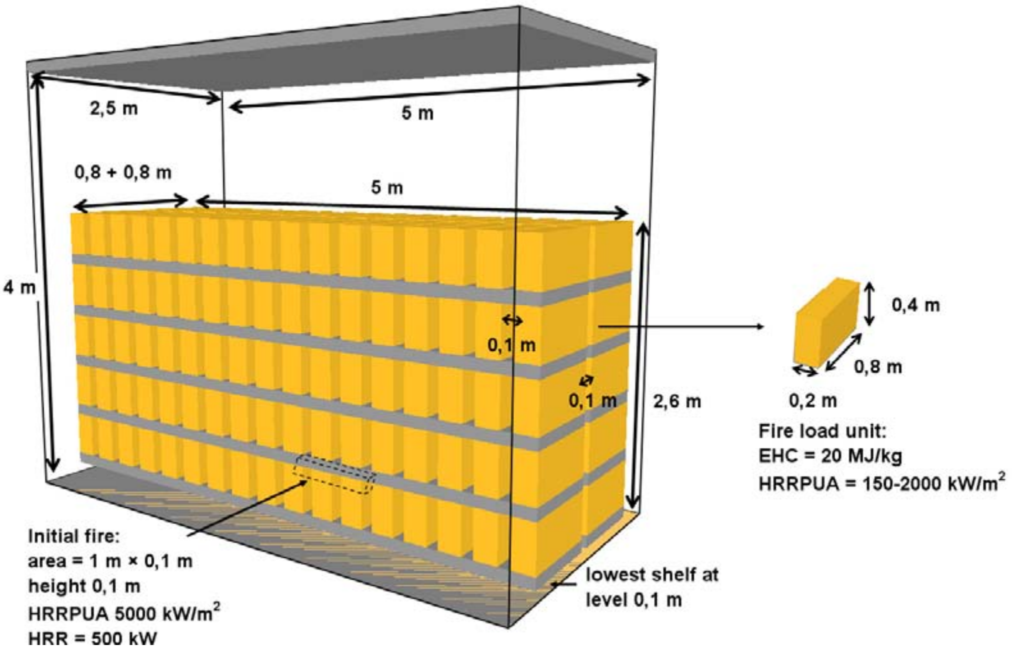
Let us consider the shelve system shown in Figure 41a. The basic fire load characteristics are

- HRRPUA:
  - 150 kW/m^2 which corresponds typically to mainly cellulosic materials such as wood and paper products.
  - 300 kW/m^2 which corresponds typically to fire load that may have cellulosic materials and some plastics which are fire-retarded or otherwise not very highly combustible like PET, POM, etc. Furniture fire load may also fall to this category (or the next category).
  - 500 kW/m^2 which corresponds to such fire loads as mixtures of cellulosic materials (major ingredient) and highly-combustible plastics such as ABS, PE, PP and PS, or fire load with plastics like PET, POM, PMMA as the principal ingredient. Furniture fire load may also fall to this category.
  - 1 000 kW/m^2 which corresponds typically to fire load that contains notable amounts of non-fire retarded high-combustible plastics like ABS, PE, PP and PS. Other ingredients may be, e.g., cardboard boxes, etc.
  - 2 000 kW/m^2 which corresponds to fire load that has a very high percentage of non-fire retarded highly combustible plastics like ABS, PE, PP and PS.
- effective heat of combustion EHC = 20 MJ/kg
- ignition temperature 320 °C
- density 500 kg/m^3
- specific heat 1 500 JK^{-1}kg^{-1}
- thermal conductivity 0.2 WK^{-1}m^{-1}
- ignition delay is taken as zero (instant ignition as the fuel surface temperature rises to the ignition temperature).

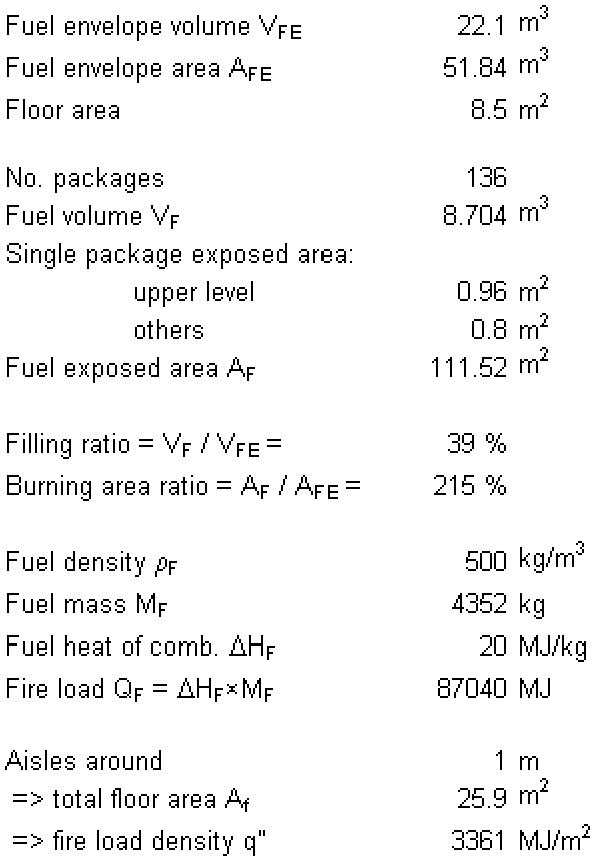
Other characteristics are summarised in Figure 41b.

The influence of the fuel HRRPUA on the strength of the fire is illustrated in Figure 42 by the comparison of HRRPUA values of 150 kW/m^2 (Figure 42a) and 1 000 kW/m^2 (Figure 42b). Figure 42 shows the state of the fire 10 minutes after ignition. It can be seen that already in this stage the fire with HRRPUA of 1 000 kW/m^2 is much more severe in terms of fire spread and smoke production than the fire with HRRPUA of 150 kW/m^2.

a)



b)



Fuel envelope volume V_{FE}	22.1	m^3
Fuel envelope area A_{FE}	51.84	m^3
Floor area	8.5	m^2
No. packages	136	
Fuel volume V_F	8.704	m^3
Single package exposed area:		
upper level	0.96	m^2
others	0.8	m^2
Fuel exposed area A_F	111.52	m^2
Filling ratio = V_F / V_{FE} =	39 %	
Burning area ratio = A_F / A_{FE} =	215 %	
Fuel density ρ_F	500	kg/m^3
Fuel mass M_F	4352	kg
Fuel heat of comb. ΔH_F	20	MJ/kg
Fire load $Q_F = \Delta H_F \times M_F$	87040	MJ
Aisles around	1	m
=> total floor area A_f	25.9	m^2
=> fire load density q"	3361	MJ/m^2

Figure 41. Model for the shop shelve fire-load unit: a) schematic presentation and b) some calculated characteristics.

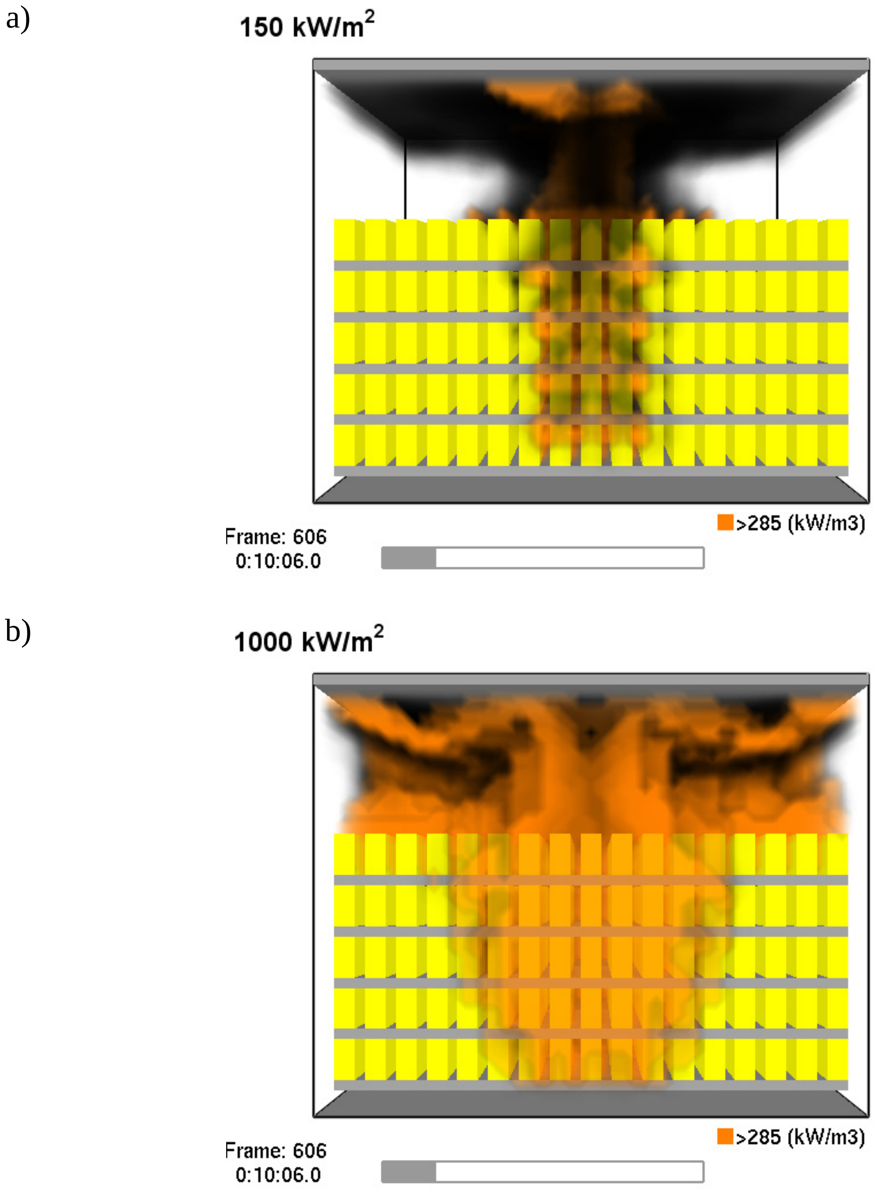


Figure 42. Illustration of the influence of the fuel HRRPUA on the strength of the fire: a) fuel HRRPUA = 150 kW/m^2 corresponding to cellulosic materials such as wood and paper products, and b) fuel HRRPUA = 1 000 kW/m^2 corresponding to fire load that contains notable amounts of non-fire retarded plastics like ABS, PE, PP and PS.

Figure 43 shows the predicted evolution of the shelf-system HRR for different values of fire load HRRPUA. It can be seen that the maximum HRR is strongly dependent on the HRRPUA value of the fire load (see Figure 43f).

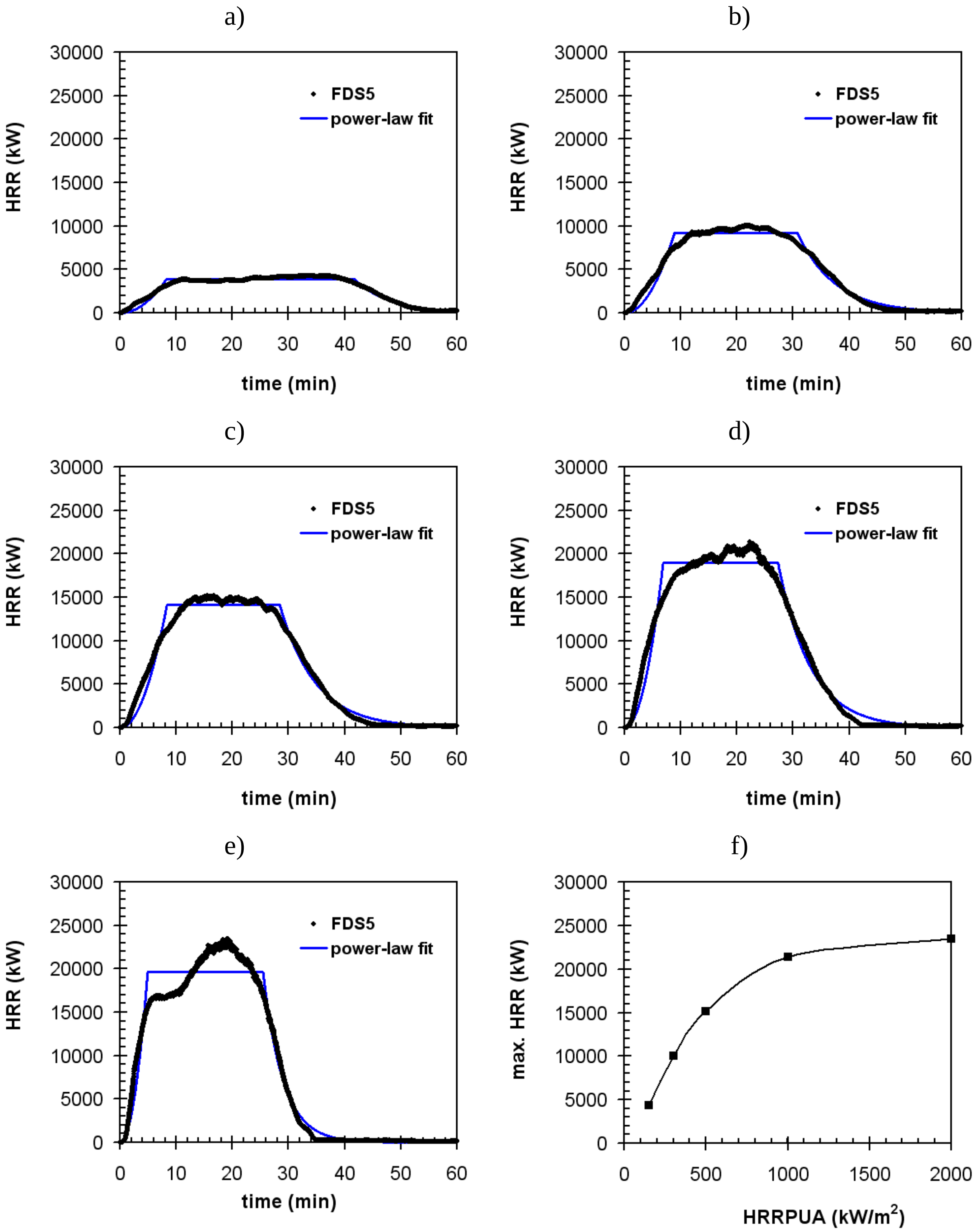


Figure 43. Evolution of shelf system HRR for different fire load HRRPUA values: a) 150 kW/m^2, b) 300 kW/m^2, c) 500 kW/m^2, d) 1000 kW/m^2, e) 2000 kW/m^2 and f) max. HRR vs. HRRPUA. The blue curves in a–e show t^2-shaped fits to the FDS results.

4. Subproject III – Structures

The objective of Subproject III – Structures was to find out critical situations for ship structures under natural fire exposure conditions by combining calculations of fire development with structural calculations. A fire situation recognised critical, an engine room fire below a car deck, was examined in detail by performing thermal and mechanical analyses of deck structures. In this chapter the problem is briefly dealt with. The study is described in detail in VTT Research Report No. VTT-R-04098-09 [49].

4.1 Effects of engine room fires on car deck structures

4.1.1 Thermal analysis of a beam-deck construction

A beam-deck construction was analysed by the FEM program COMSOL Multiphysics [50]. As a result of the analysis, the temperature field of a beam-deck was derived as a function of time. The analysis was performed using two dimensional heat transfer model which takes into account conduction, convection and radiation.

4.1.1.1 Beam-deck constructions

The beam-deck construction studied comprises of an insulated I-beam and a deck. A drawing of the construction is presented in Figure 44. The dimensions of the bottom flange, web and deck used in ships vary. Typical values are presented in Table 13. The steel grade is S355. The beam and deck are insulated with rock wool of the fire resistance class A60. The density of the rock wool is 100 kg/m^3 and the thickness 40 mm or 25 mm.

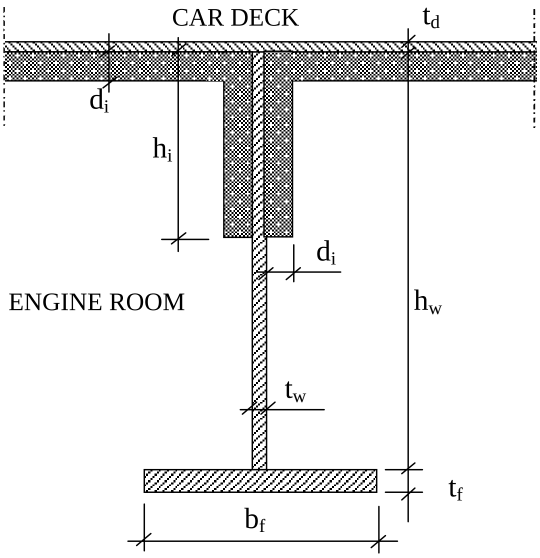


Figure 44. Beam-deck construction.

Table 13. Dimension of bottom flange, web and deck (in mm).

Bottom flange $b_f \times t_f$	**Web $h_w \times t_w$**	**Deck t_d**
100 × 15 150 × 15 200 × 15 300 × 20 **400 × 20**	**400 × 10** 600 × 10 800 × 10 900 × 10 **1200 × 12**	**10** / 15 / **20**

Two beam-deck constructions were analysed: the maximum (blue) and minimum (red) dimensions of the construction in Table 13.

4.1.1.2 Thermal material properties

The following thermal material properties were used when calculating temperatures:

Steel: Thermal conductivity, specific heat and density $\rho = 7\,850$ kg/m^3 were according to SFS-EN 1993-1-2: 2002 [51] as well as emissivity $\varepsilon = 0.7$.

Rock wool: Density of rock wool $\rho = 100$ kg/m^3 and specific heat $c_p = 830$ J/kgK [52]. Thermal conductivity is assumed to vary as presented by Ranby [53] so that the temperatures calculated and measured in a fire resistance test are in good agreement. The thermal conductivity used in the temperature calculations (“lambda 100 (W/mK) laiva”) as well as the conductivity of rock wool with different densities [53] are presented in Figure 45. The emissivity of rock wool is $\varepsilon = 0.7$.

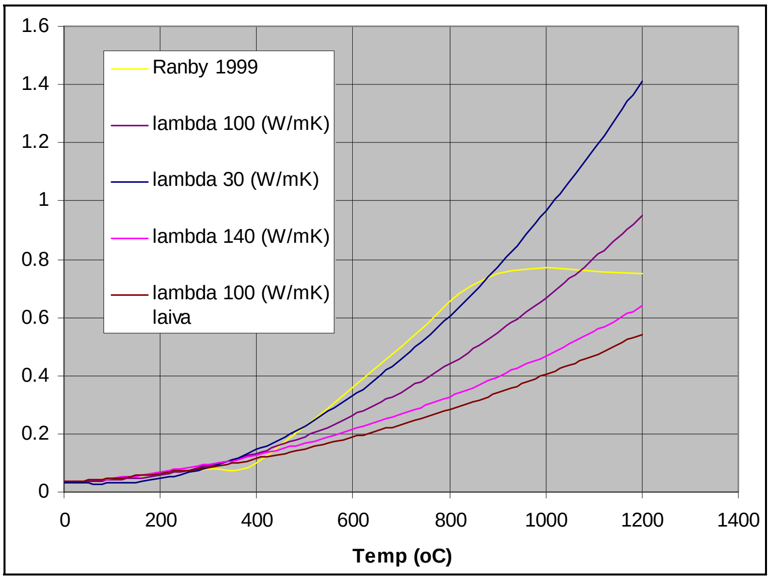


Figure 45. Thermal conductivity of rock wool with different densities as a function of temperature. The curve ”lambda 100 (W/mK) laiva” is used in the calculations.

4.1.1.3 Fire exposure

Fire exposure according to the IMO FTP Code Part 3 [1, pp. 12–17 and 127–173] (ISO 834-1: 1999 [54], EN 1363-1:1999 [55]) (in the following IMO-curve) is used when structures are classified. Fire exposure according to hydrocarbon time-temperature curve (HC-curve) of the standard EN 1363-2:1999 [56] is also possible in the engine room. Both the IMO-curve and the HC-curve were used in this analysis. The curves are shown in Figure 46.

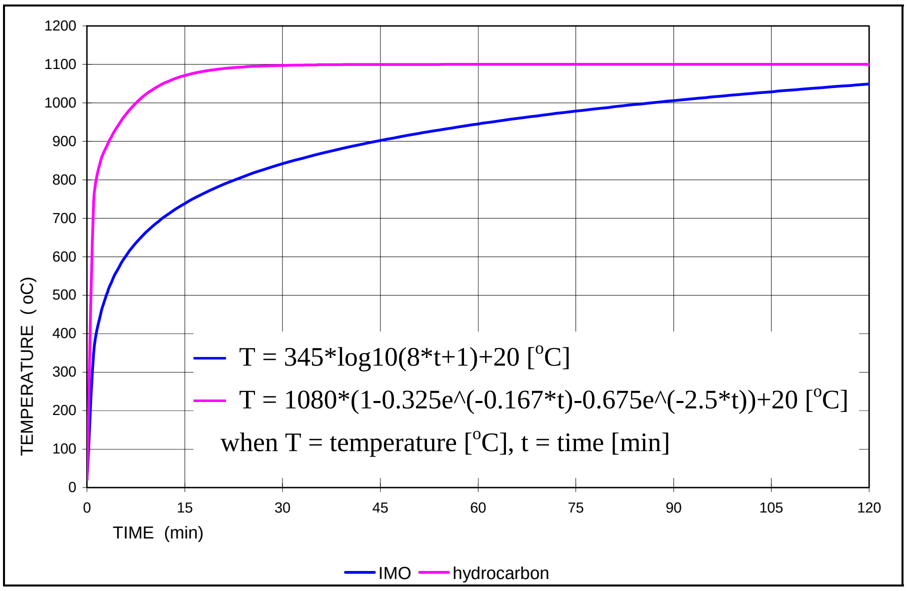


Figure 46. Fire exposures according to IMO FTP Code Part 3 [1, pp. 12–17 and 127–173] and hydrocarbon time-temperature curve of standard EN 1363-2:1999 [56].

4.1.1.4 Boundary conditions

In the thermal analysis, the coefficient of heat transfer by convection was α_c= 25 W/m^{2}K on the exposed side and α_c= 4 W/m^{2}K on the unexposed side [57] when the temperature increased according to the IMO-curve. When the temperature increased according to HC-curve, the coefficient of heat transfer by convection was α_c= 50 W/m^{2}K on the exposed side.

4.1.1.5 Calculation model

Three cases were calculated: the beam was insulated 450 mm along the web (case A), along the whole web (case B), or the whole section was insulated (case C).

The geometry and the element mesh of two beam-deck constructions are presented as examples in Figure 47: the maximum beam with insulation length of 450 mm along the web (case A) and the minimum beam with insulation around the whole section (case C). The width of the deck in the figures is 800 mm and the thickness of the insulation is 40 mm.

Maximum and minimum beam-deck constructions were analysed using thermal material properties and boundary conditions presented above in all insulation cases A, B and C when the fire exposure was according to the IMO-curve or the HC-curve. The ambient temperature in the engine room and on the car deck was 20 °C in the calculations.

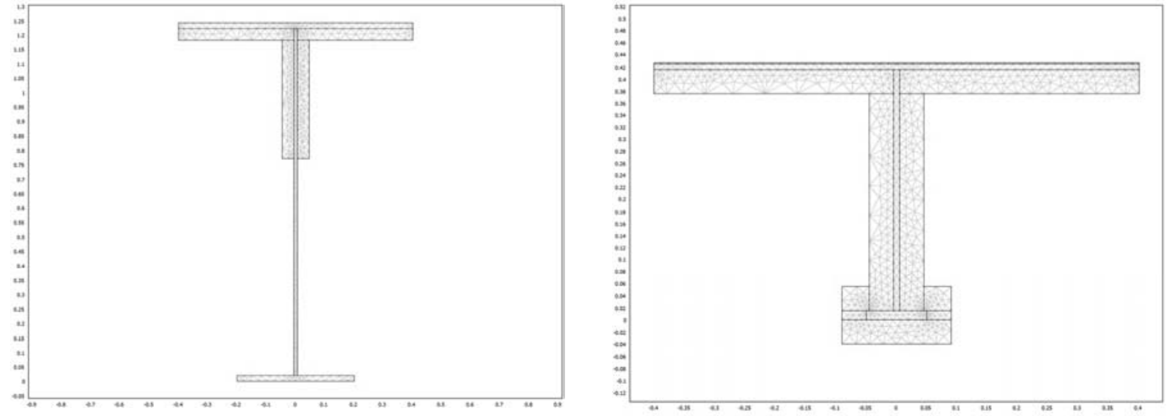


Figure 47. Element mesh of the maximum beam-deck construction with insulation length of 450 mm (case A, left) and the minimum beam-deck construction with insulation around the section (case C, right).

4.1.1.6 Results of thermal analysis and comparison of temperatures

The temperature fields of the maximum and minimum sized beam-deck constructions with 40 mm thick insulation at the time of 60 minutes in cases A and C are presented in Figures 48 and 49 when the fire exposure was according to the IMO-curve. Temperatures were calculated in the points presented in Figures 48 and 49.

Temperatures at 60 minutes when fire exposure according to IMO-curve:

The temperature of the uninsulated area of the steel section was about 900 °C, and the temperature of the insulated area varied in the range of about 150–900 °C. The temperatures of the totally insulated sections remained below 350 °C.

Temperatures at 60 minutes when fire exposure according to HC-curve:

The temperature of the uninsulated area of the steel section was about 1 000–1 100 °C, and the temperature of the insulated area varied in the range of about 250–1 100 °C. The temperatures of the totally insulated sections were about 250–300 °C in the deck and 430–550 °C elsewhere.

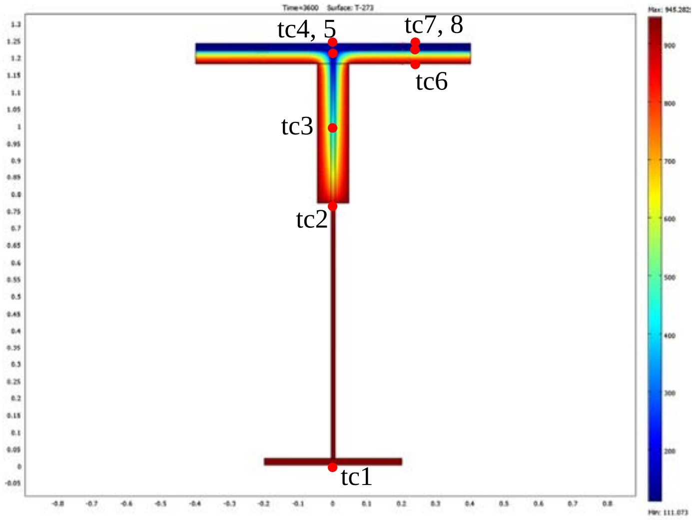


Figure 48. Temperature field of the beam-deck (deck t_d = 20 mm, web $h_w \times t_w$ = 1 200 × 12 mm^2, bottom flange $b_f \times t_f$ = 400 × 20 mm^2) with 40 mm thick insulation in case A.

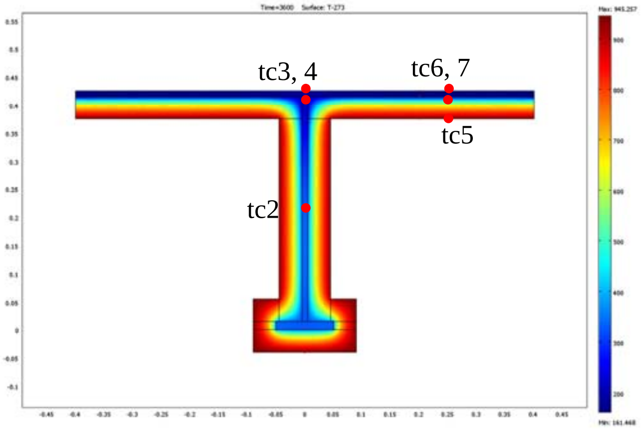


Figure 49. Temperature field of the beam-deck (deck t_d = 10 mm, web $h_w \times t_w$ = 400 × 10 mm^2, bottom flange $b_f \times t_f$ = 100 × 15 mm^2) with 40 mm thick insulation in case C.

Comparisons of the calculated temperatures of the beam-deck constructions when the fire exposure is according to the IMO-curve or the HC-curve are presented in Figures 50–54. In both cases, the temperatures of the sections rise in the same way, but when the fire exposure is according to the HC-curve, the temperature rise is quicker and the temperatures are higher. The temperature difference is about 200 °C at the bottom flange and the web, and about 100 °C at the deck at the time of 60 minutes.

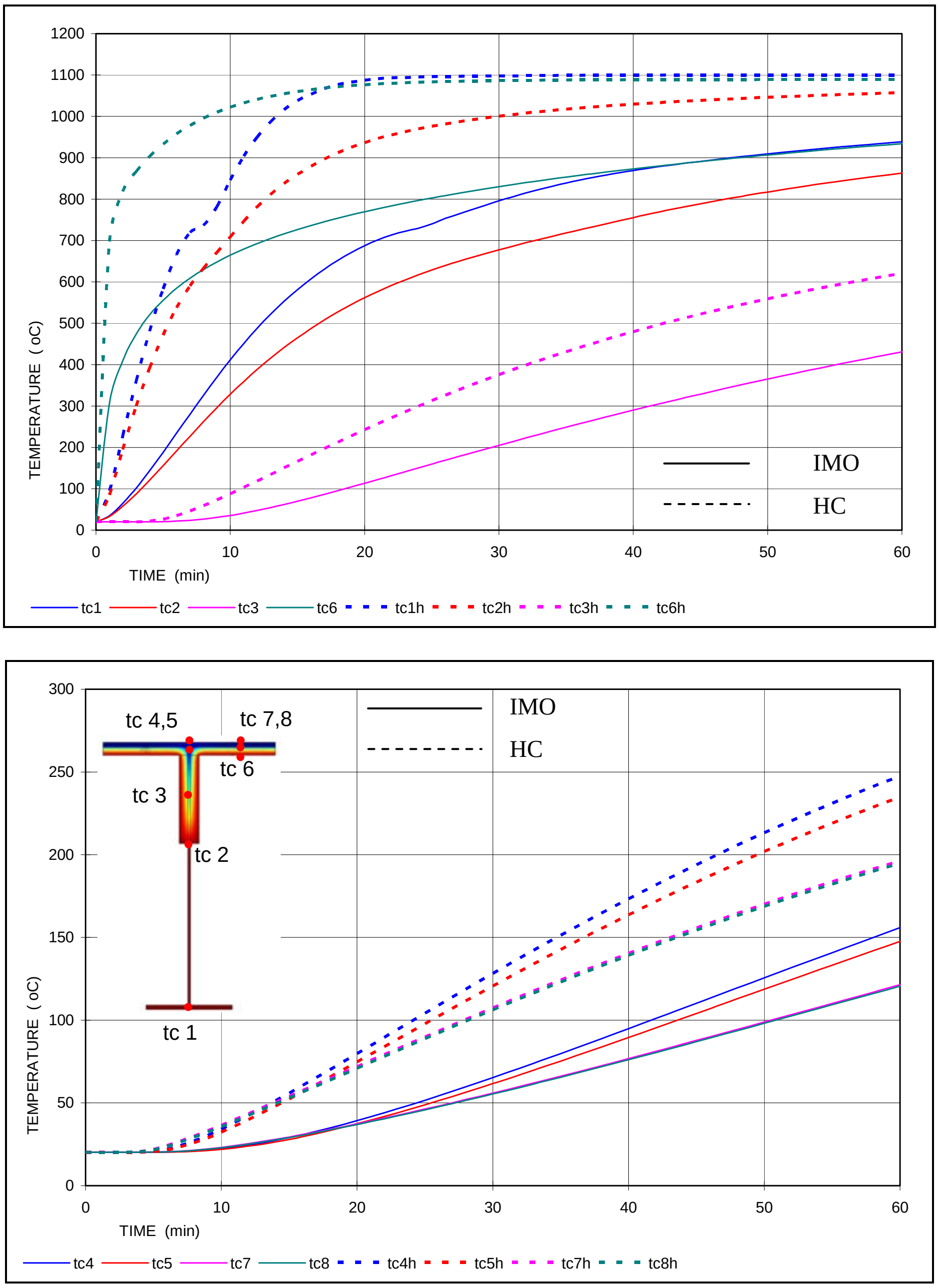
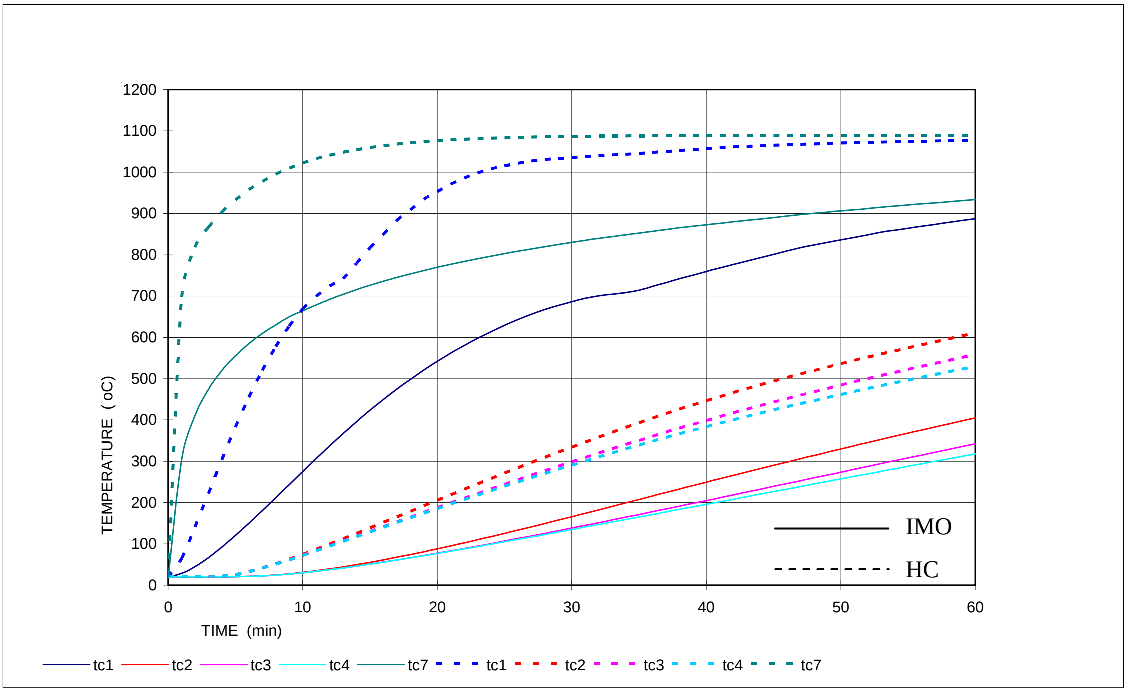


Figure 50. Comparison of the temperatures of the beam-deck (deck t_d = 20 mm, web $h_w \times t_w$ = 1200 × 12 mm^2, bottom flange $b_f \times t_f$ = 400 × 20 mm^2) with 40 mm thick insulation in case A when fire exposure according to IMO-curve or HC-curve.



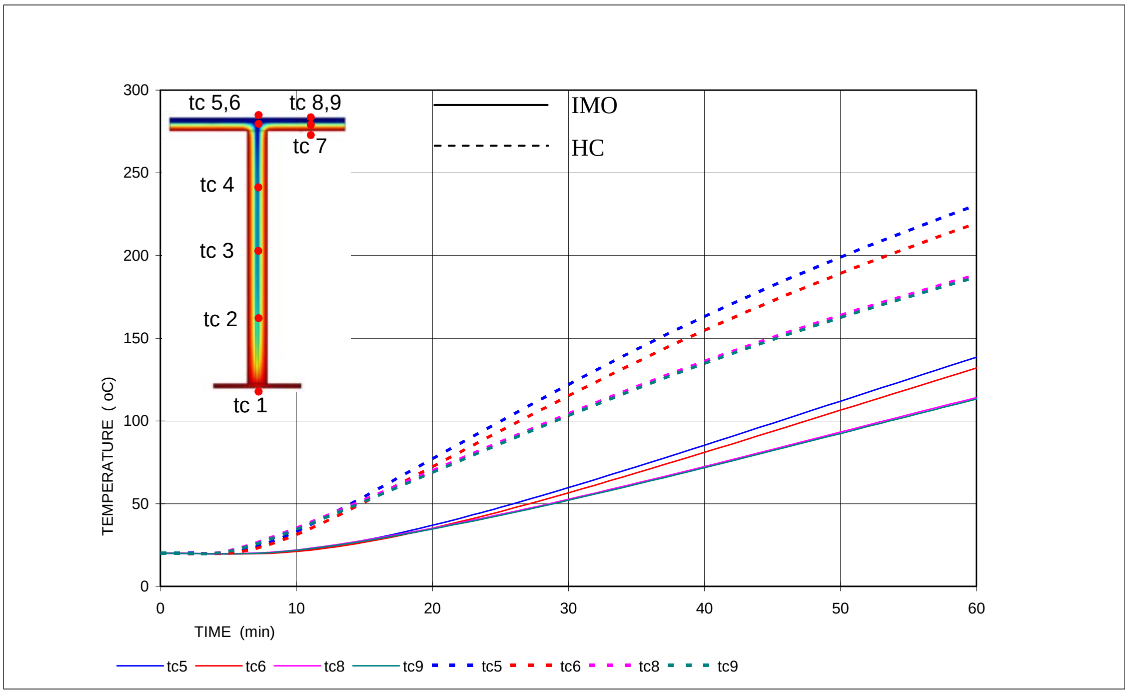


Figure 51. Comparison of the temperatures of the beam-deck (deck t_d = 20 mm, web $h_w \times t_w$ = 1200 × 12 mm^2, bottom flange $b_f \times t_f$ = 400 × 20 mm^2) with 40 mm thick insulation in case B when fire exposure according to IMO-curve or HC-curve.

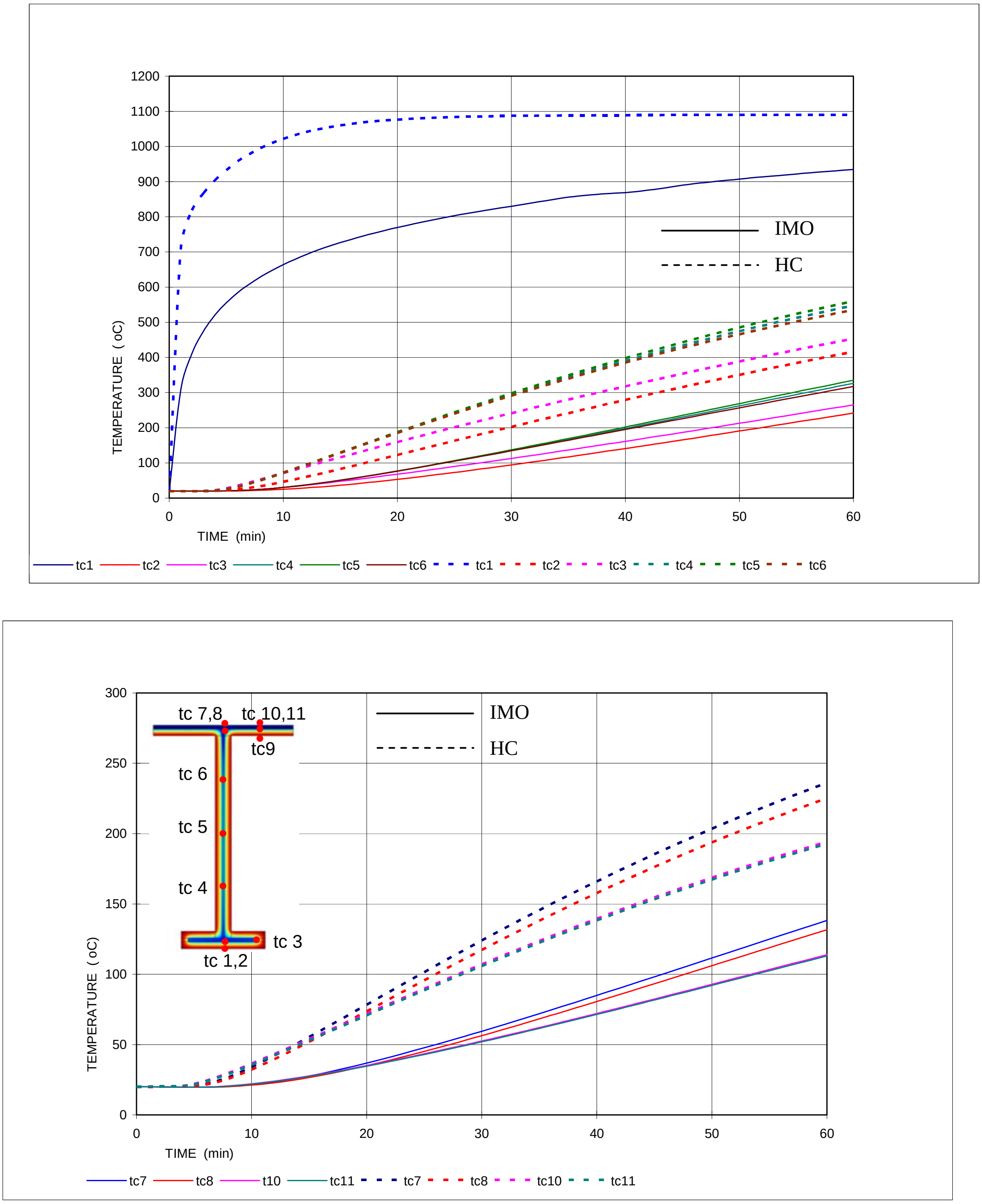
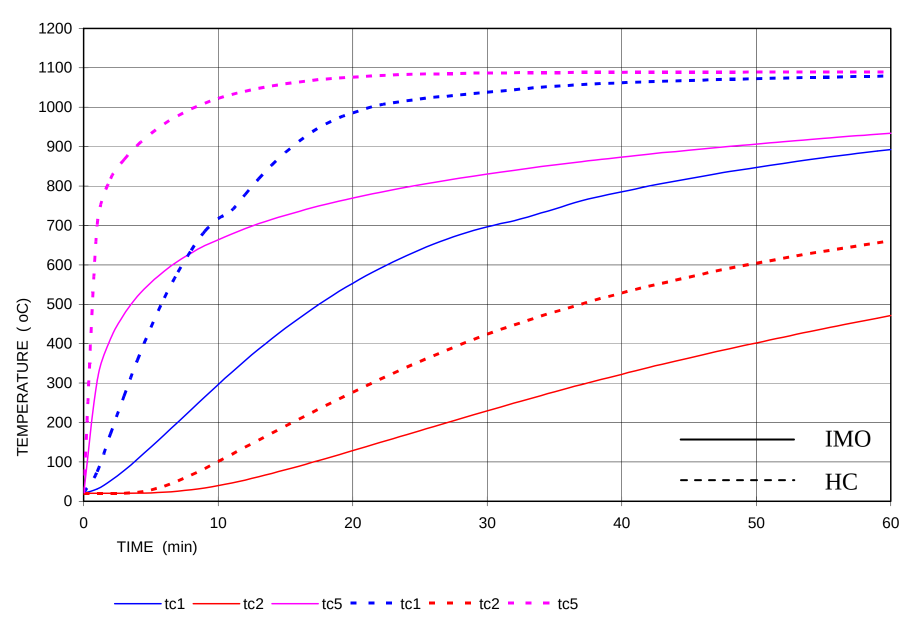


Figure 52. Comparison of the temperatures of the beam-deck (deck t_d = 20 mm, web $h_w \times t_w$ = 1200 × 12 mm^2, bottom flange $b_f \times t_f$ = 400 × 20 mm^2) with 40 mm thick insulation in case C when fire exposure according to IMO-curve or HC-curve.



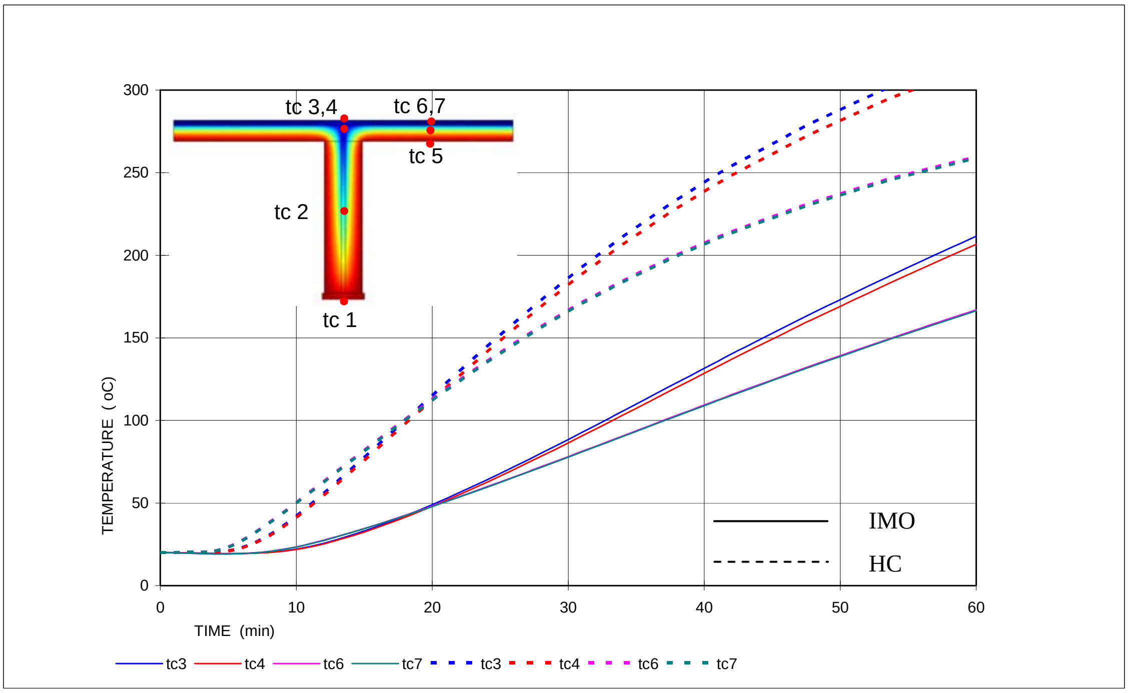
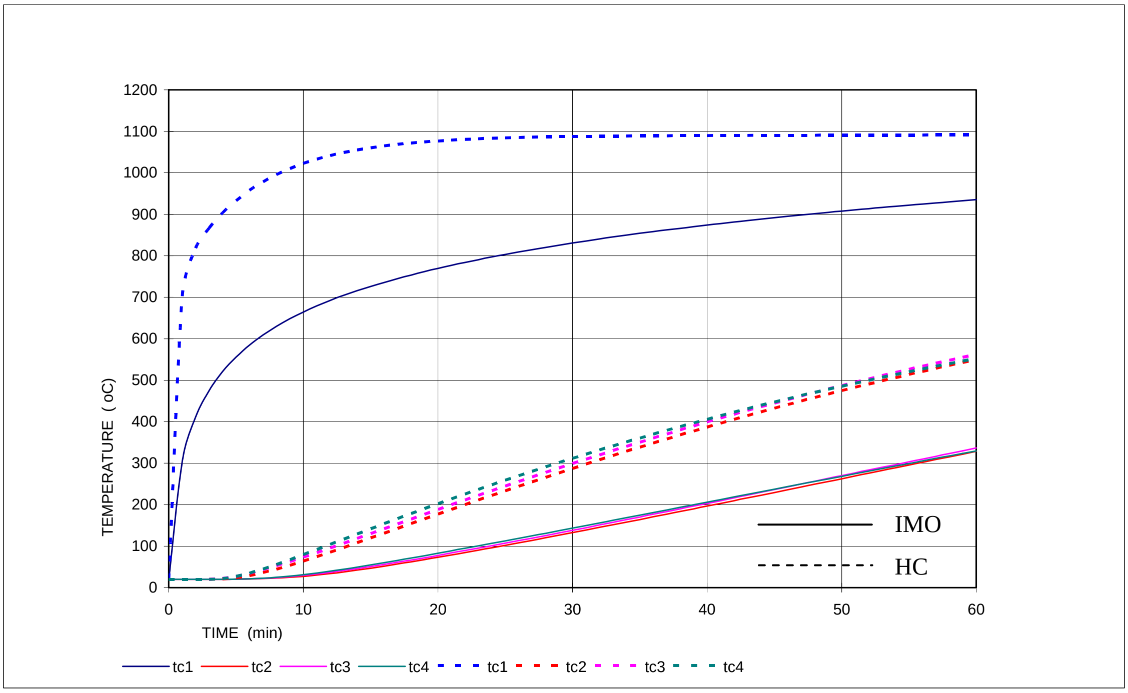


Figure 53. Comparison of the temperatures of the beam-deck (deck t_d = 10 mm, web $h_w \times t_w$ = 400 × 10 mm^2, bottom flange $b_f \times t_f$ = 100 × 15 mm^2) with 40 mm thick insulation in case B when fire exposure according to IMO-curve or HC-curve.



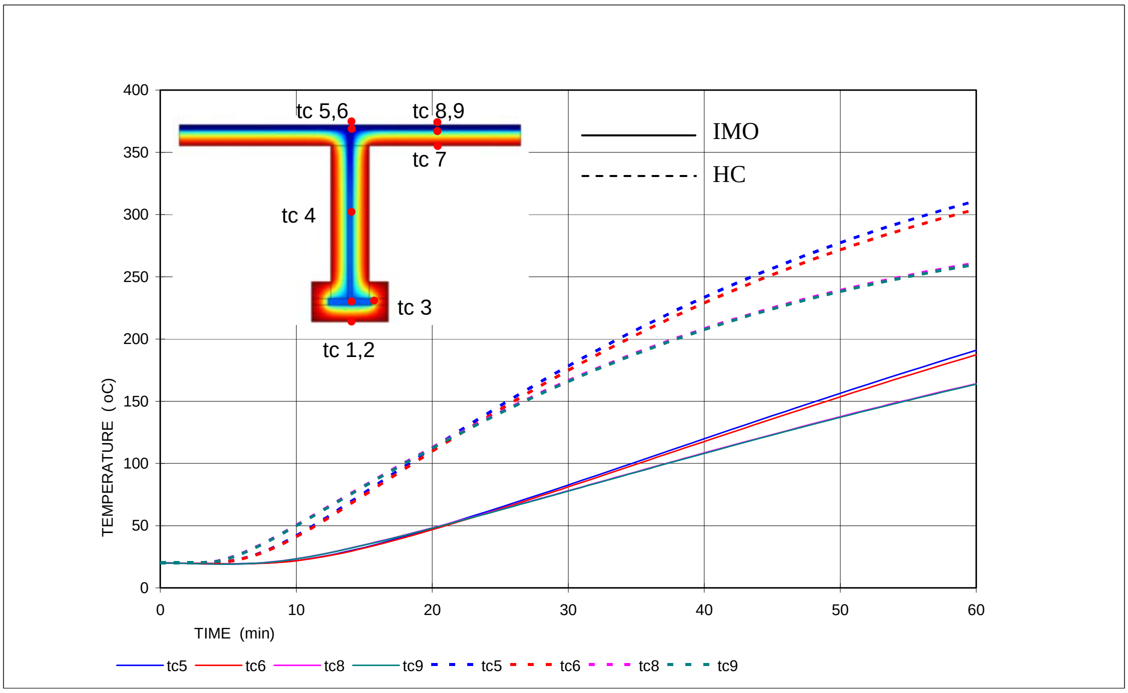


Figure 54. Comparison of the temperatures of the beam-deck (deck t_d = 10 mm, web $h_w \times t_w$ = 400 × 10 mm^2, bottom flange $b_f \times t_f$ = 100 × 15 mm^2) with 40 mm thick insulation in case C when fire exposure according to IMO-curve or HC-curve.

4.1.2 Mechanical analysis of beam-deck constructions

Mechanical analysis was performed on the same beam-deck sections by the Excel program using the above-calculated temperatures of the beam-deck constructions.

4.1.2.1 Mechanical material properties

Steel strength and modulus of elasticity reduce at elevated temperatures. Reduction factors for the stress-strain relationship for steel at elevated temperatures are given in Figure 55 according to the standard EN 1993-1-2:2002 [51]. The reduction factors are defined as follows:

- effective yield strength relative to yield strength at 20 °C $k_{y,\theta} = f_{y,\theta} / f_y$
- slope of linear elastic range relative to slope at 20 °C $k_{E,\theta} = E_{a,\theta} / E_a$.

The strength of steel decreases rapidly after the temperature of 400 °C, and the modulus of elasticity starts to decrease after 100 °C, at first slowly but after 500 °C rapidly.

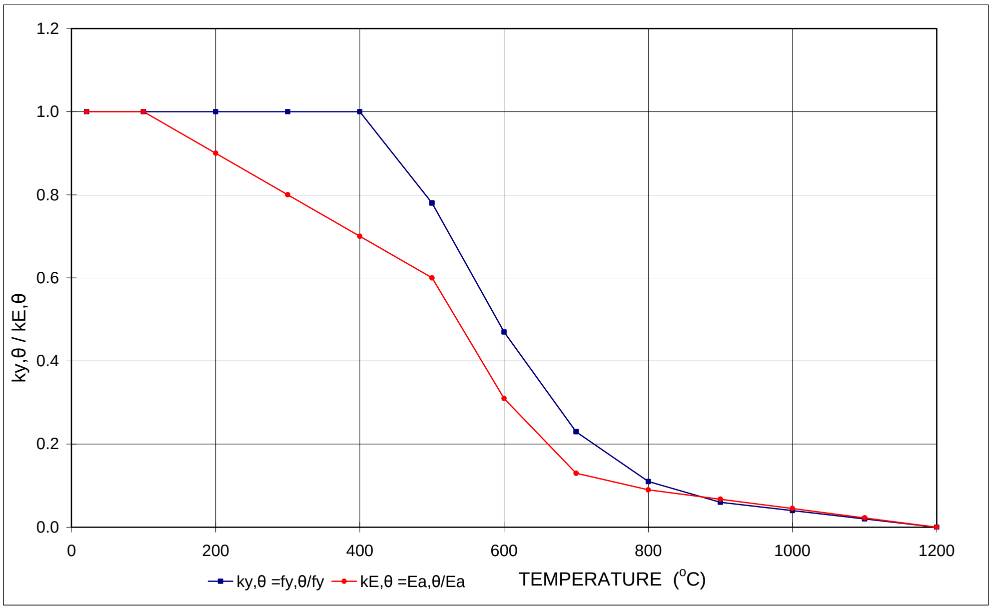


Figure 55. Reduction factors for the stress-strain relationship at elevated temperatures.

4.1.2.2 Loadbearing capacity of beam-deck constructions

The steel section was divided into elements depending on the temperature distribution along the section. For example in case A, the flange and the deck of the maximum beam-deck construction was one element, the uninsulated part of the web was divided into three elements, and the insulated part into four elements. The strength of each element changed according to the temperature of the element. The proportional moment capacity (moment capacity as a function of time / moment capacity at room temperature) of the maximum beam-deck construction as a function of time is presented in Figure 56.

When the fire exposure rises according to the IMO-curve, the moment capacity begins to decrease at the time of 10 minutes, and after 30 minutes about 25 % of the moment capacity is left. When the fire exposure rise according to the HC-curve, the moment capacity begins to decrease already after a few minutes, and after 10 minutes about 20 % of the moment capacity is left.

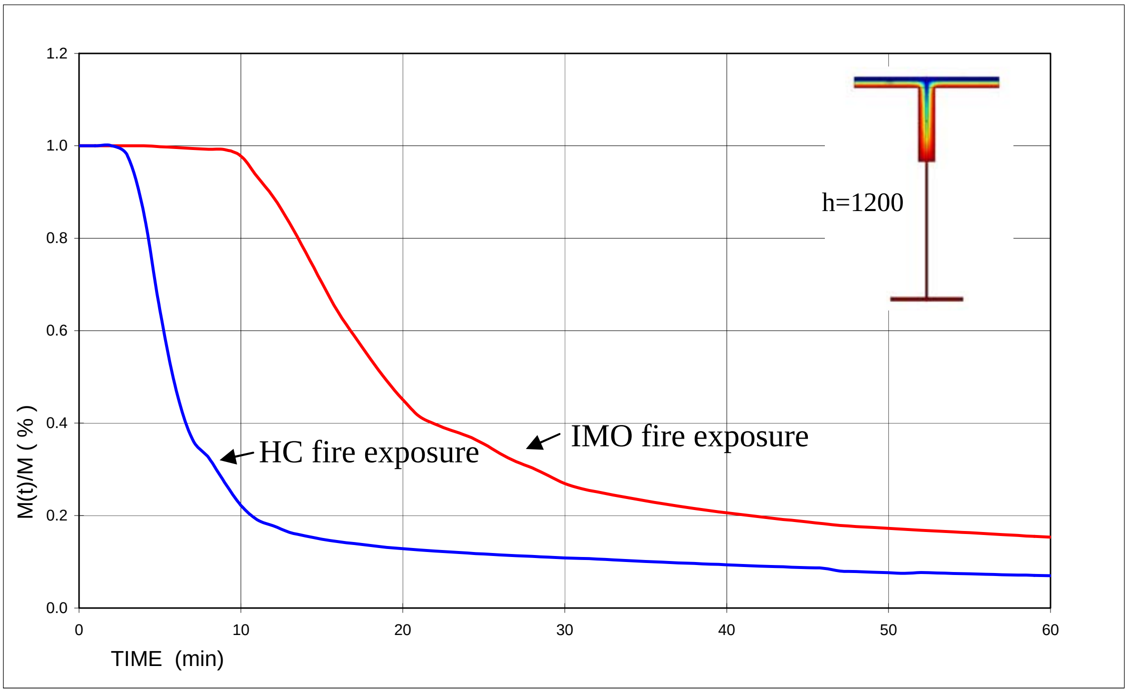
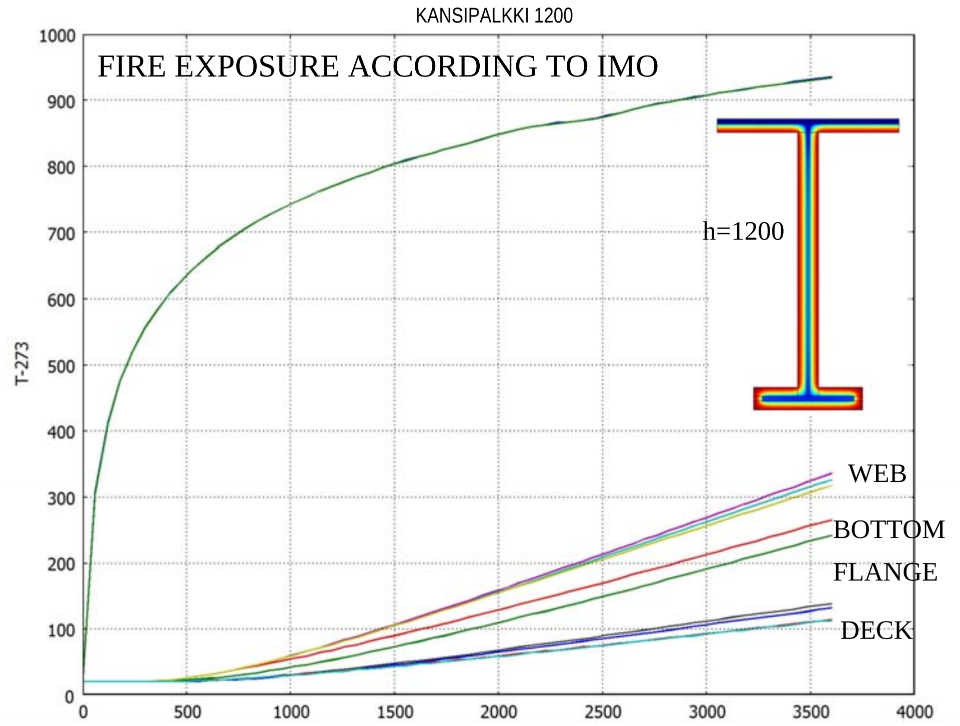
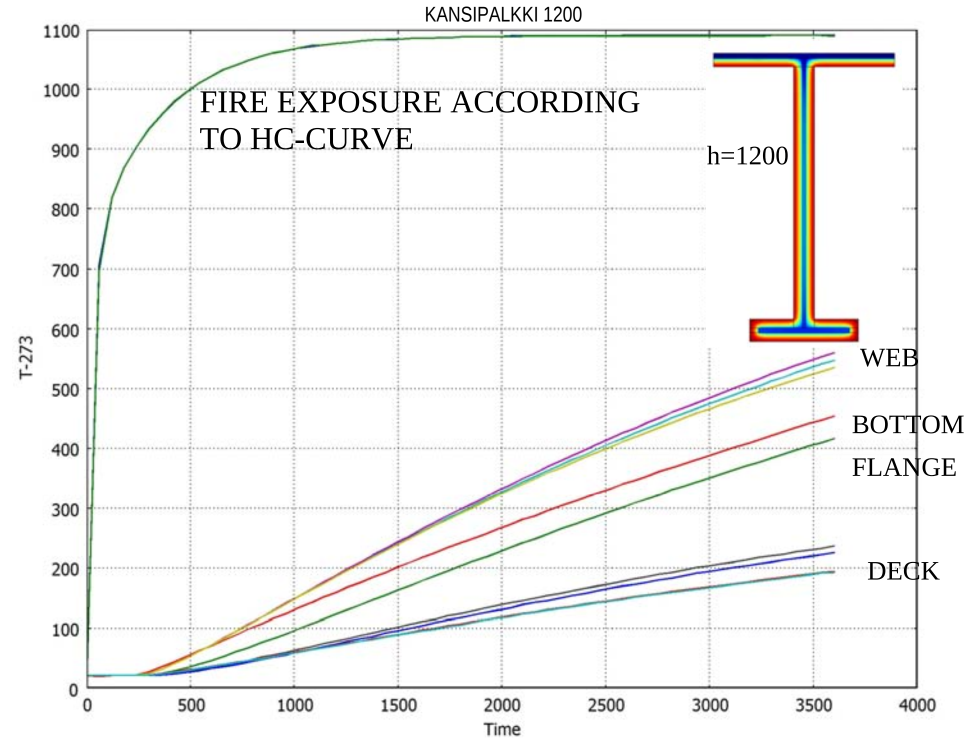


Figure 56. Proportional moment capacity decrease as a function of time when the temperature increases according to IMO-curve or HC-curve.

On the basis of the temperatures of the section, it can be estimated if the decrease of the moment capacity is significant, because the strength starts to reduce after 400 °C. In Figures 57 and 58, the moment capacity decrease is estimated for the totally insulated maximum and minimum beam-deck sections, respectively.

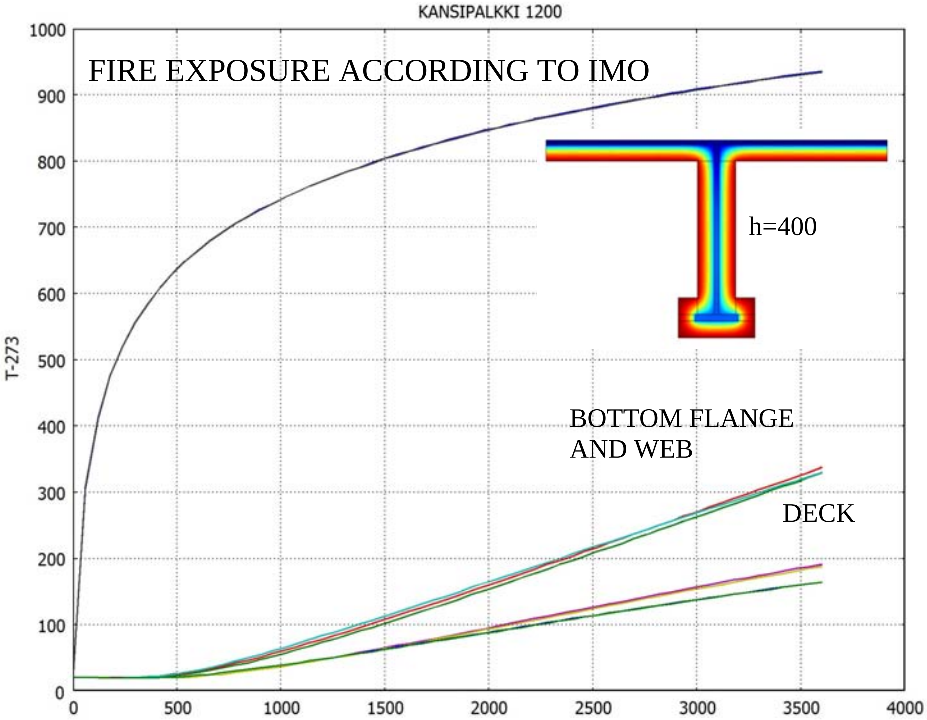


NO DECREASE IN THE CAPACITY (60 min)

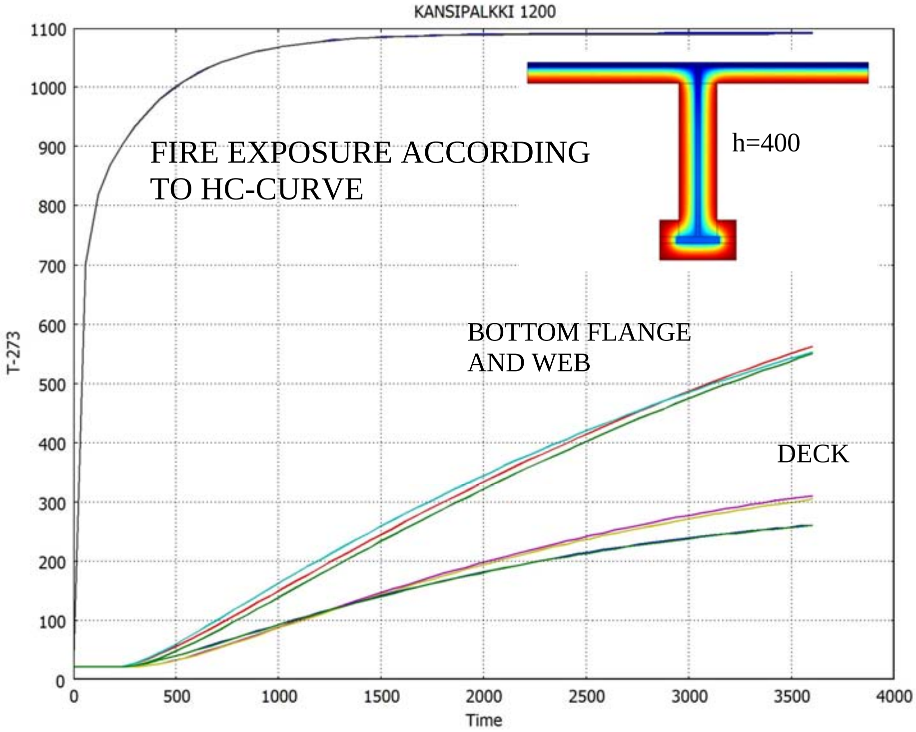


SOME DECREASE IN THE CAPACITY (60 min)

Figure 57. Temperatures of the totally insulated maximum beam-deck section (C) and the effect of temperatures on the moment capacity when the temperature increases according to IMO-curve or HC-curve.



NO DECREASE IN CAPACITY (60 min)



SIGNIFICANT DECREASE IN CAPACITY (60 min)

Figure 58. Temperatures of the totally insulated minimum beam-deck section (C) and the effect of temperatures on the moment capacity when the temperature increases according to IMO-curve or HC-curve.

4.2 Fire conditions critical for structures

4.2.1 Performance criteria for insulation

The performance criteria of insulation for “A” class divisions, including “A” class doors, are defined in the IMO FTP Code Part 3 [1, pp. 12–17 and 127–173]. The average unexposed-face temperature rise should not be more than 140 °C, and the temperature rise in any location on the unexposed-face should not be more than 180 °C during certain time periods, e.g. 60 minutes for class “A-60”.

The ambient temperature in the calculations was 20 °C which means that the average temperature should not be more than 160 °C, and the maximum temperature not more than 200 °C. All calculated temperatures of the maximum sized beam-deck remained below 150 °C on the unexposed side of the deck in cases A, B and C (see section 4.1.1.6). Thus, the insulation criteria were fulfilled.

The average temperature of the minimum sized beam-deck on the unexposed side was 173 °C in case B and 164 °C in case C. The maximum temperature was 212 °C in case B and 187 °C in case C. In either case, the insulation criteria were not fulfilled.

In the calculations it was assumed that the insulation stays in its position and no cracks or gaps emerge e.g. between insulation joints during the fire. The effect of shrinkage of rock wool is taken into account to some extent because the conductivity of the insulation was defined on the basis of a fire resistance test of a deck. However, the deck is unloaded during the test, and deformations remain small compared to practice.

4.2.2 Performance of loadbearing beam-deck constructions

The fire exposure according to the IMO FTP Code Part 3 [1, pp. 12–17 and 127–173] is used when structures are classified. Engine room fires are often oil mist fires which are described quite well by the fire exposure according to the hydrocarbon time-temperature curve of standard EN 1363-2:1999 [56].

If a fire extinguishing system of the engine room operates immediately after the start of the fire, the temperatures in the engine room remain low. However, if the system does not work, or the system is based on e.g. carbon dioxide when the system is discharged after about 20 minutes, the temperatures in the engine room rise rapidly. In this case, fire exposure according to IMO-curve or HC-curve is relevant, and the rapid decrease of the moment capacity is possible already in the beginning of the fire.

Mechanical analysis of the beam-deck constructions was discussed in section 4.1.2. The beam and the deck were insulated using 40 mm thick rock wool with the density of 100 kg/m^3. The following conclusions can be made:

Totally insulated sections:

- The temperatures of the totally insulated steel sections remain below 400 °C when the fire exposure of 60 minutes is according to the IMO-curve. Thus, the moment capacity of the beam does not decrease. However, small deformations can emerge because the modulus of elasticity decreases after 100 °C.

- The temperatures of the totally fire protected steel sections remain below 600 °C when the fire exposure of 60 minutes is according to the HC-curve. In this case, the decrease of the moment capacity depends on the size of the section and it can be significant.

Partially insulated sections:

- The temperatures of the partially fire protected steel sections increase so high in the bottom flange and uninsulated web that the moment capacity starts to decrease rapidly within 15 minutes or 5 minutes when the fire exposure is according to the IMO-curve or the HC-curve, respectively (see Figure 56). After 30 minutes, about 25 % of the moment capacity is left when the fire exposure is according to the IMO-curve. After 10 minutes, about 20 % of the moment capacity is left when the fire exposure is according to the HC-curve. So the failure of the beam occurs long before 60 minutes.

As a consequence of the decrease of the moment capacity, the beam-deck deflects causing cracks and gaps in fire protection, or even total break-off of the protection. This has also significant effect on the temperature field of the deck, and the temperatures will be higher than the calculated temperatures in section 4.1.1.

5. Subproject IV – Evacuation

The main objective of Subproject IV – Evacuation was to ensure the applicability of the novel evacuation simulation method FDS+Evac for ships, considering the requirements by the design practitioners and those given by Annex 3 of IMO MSC.1/Circ.1238 [58]. The specific features of ships to be considered in evacuation studies were detected. A new staircase model was developed to facilitate the description of complex staircases in egress simulation.

5.1 Specific features of ship evacuation

5.1.1 Background

Numerical simulation of emergency evacuation has been used for years to design the fire and evacuation safety aspects of buildings and transportation vehicles. Typically, the design process is based on the RSET-ASET principle, which states that the Required Safe Egress Time (RSET) should be smaller than the Available Safe Egress Time (ASET). The RSET is typically given by the evacuation simulations and ASET by fire or flooding simulations as a time to reach life-threatening conditions.

The evacuation simulations are often performed as a part of the formal safety assessment. The goals for the modern evacuation analysis for cruise ships were recently outlined in [59] and for land-based buildings [60]. According to these suggestions, the risk for human life should be studied in terms of F-N curve which relates the probability of N fatalities to the commonly accepted risk level of the society. F-N curves have been used in process and nuclear industry for decades, but not in the building design. To meet these goals, it will be necessary to perform the evacuation computations in a probabilistic manner, requiring hundreds of simulations for each scenario.

In the recent review of ship evacuation models [61], 28 ship evacuation models were examined and categorized according to their original application area, the representation of geometry, the level of verification in light of IMO MSC Circular 1033 (the predecessor of [58]), the ability to represent environmental conditions, and the inclusion of maritime specific procedural tasks and configuration entities. Similar review of building evacuation models was recently published by the SFPE [62].

Despite the obvious interactions between fire spread and evacuation, these two processes have usually been simulated using separate numerical tools. One of the few evacuation models capable of full interaction with a fire model is the FDS+Evac model developed at VTT [44]. The multidisciplinary development of FDS+Evac took off in the project (2005–2007) funded by the Modelling and Simulation Technology Program (MASI) of TEKES [63]. The psychological aspects of evacuation were then reviewed by the Department of Social Psychology, University of Helsinki, and the game-theoretic modelling was started at the Systems Analysis Laboratory, Helsinki University of Technology (TKK).

5.1.2 Ship-specific features for FDS+Evac

Due to the wide range of existing ship evacuation models, there is no particular need to make all the ship-specific features that were listed in [61], available in FDS+Evac. Instead, a query was sent to the members of the project steering committee and the industry partners of FDS+Evac development. The most recent experiences of those responding included evacuation studies of navy ships, two very large passenger ships and Ro-Pax ferry evacuation. In these studies, the number of evacuees ranged between 1 000 and 8 000. The human thresholds were computed using smoke (CO, CO_2, visibility and temperature) information saved from the fire simulations on several locations of the ship. The FED concept was not used. Typically, the analysis involved full evacuation of the ship in order to reveal the bottle necks of all decks if zone in fire. The ship design engineers gave the highest priority to the fulfilment of IMO MSC/Circ. 1033 with respect to

- definition of ship layout and IMO scenarios, staircases
- inclusion of ship crew members
- counterflow effects, life jacket pick-up
- specification of availability for primary and secondary exit routes
- specification of human properties (crew roles, reduction of "lost" passengers due to the crew actions)
- initial placement of passengers
- specification of reaction times
- speed of modelling, because IMO requires modelling of the complete ship
- interfacing with ship product models would allow performing the evacuation simulations in the early phase of the design process.

Considering the current development focus of FDS+Evac and the query responses, the following development topics were identified:

D1. Efficient yet powerful model for staircases. Since the evacuation of a passenger ship relies heavily on the use of staircases, an economic way to simulate them is needed. Due to the structural complexity of the ships, the definition of staircases and their connections to the decks may be very tedious. Up until now, two methods were available in FDS+Evac for staircase simulations: one too simple and one too complicated.

D2. Definition of the “lost” passengers. The implications would be

   a. agents having no active target
   b. importance of the majority and minority effects, herding behaviour
   c. the spreading of information among passengers is needed.

D3. Definition of a “crew member” human type. The implications would be

   a. guidance of the “lost” passengers
   b. faster spreading of correct information among the evacuees
   c. effects on the route selections.

D4. Improvement of the counterflow simulations.

D5. Interfacing or interoperability with product models.

Due to the limited resources within the SURSHIP project, the decision was made to focus on topic D1. Topics D2 and D3 will be dealt with in a bit longer timeframe by the ongoing co-operation between VTT and TKK. Topic D4 has recently been studied by Dr. Timo Korhonen outside the project. Currently, there are no plans to account for topic D5.

5.2 Staircase model

5.2.1 Objectives

The new staircase sub-model was designed with the following objectives in mind:

O1. simple user input
O2. possibility for varying stair / landing sizes and orientations
O3. crowd dynamics effects should be taken into account in a computationally efficient way
O4. fire and smoke effects
O5. the sub-model should be verified and validated before the expected use.

5.2.2 Method

To meet the first objective O1, only limited geometrical alternatives were allowed. An assumption was made that the staircase can be construed by repeating a pattern *landing-stair-landing*, as illustrated in Figure 59. This basic pattern can be repeated as many times as necessary. Figure 59, for instance, shows three repeating patterns, with second and third landings being common to two patterns. To simplify the user input, the model was equipped with a capability to automatically detect connecting doors, exits and entries. The detection is made on geometrical basis using the co-ordinates of the DOORs, EXITs and ENTRies.

The free walking speed inside the staircase can be different from the free walking speed in normal conditions. This difference can be specified separately for downwards, upwards and horizontal (landings) directions. The corresponding input keywords are `FAC_V0_DOWN, FAC_V0_UP, FAC_V0_HORI.`

The staircase tries to automatically detect the target landings for the agents by comparing the z-coordinates of the available EXITs to the landing heights. Therefore, the user does not need to explicitly specify where each agent should go. This automatic exit-detection can of course be overriden by enforcing a certain target exit.

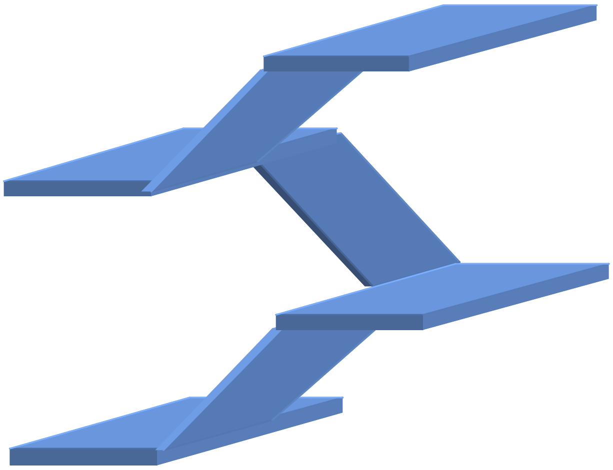


Figure 59. Repeating pattern of landings, stairs and landings.

Below is an example of the user input defining the staircase. Additionally, a separate evac-mesh is needed, and the internal obstacles must be explicitly defined to prevent the agents from walking outside the stairs and landings.

```
&STRS       ID = 'Stairs’
            XB = 5,8.5,0,2.5,0,13
            XB_CORE = 6,7.5,1.2,1.3
            RIGHT_HANDED = .TRUE.
            MESH_ID = 'Stair_mesh’
            N_LANDINGS = 7
            VERTICAL_LANDING_SEPARATION = 1.5
            XB_LANDINGS(1,:)=5.0,6.0,0,2.5,0.9,1.1
            XB_LANDINGS(2,:)=7.5,8.5,0,2.5,2.4,2.6 /
```

Obviously, the objectives O1 and O2 are somewhat in conflict. The first objective was ranked to be more important than the second one, and as a consequence, the possibilities for geometrical variations are quite limited. The possible variations include only the size of the staircase (independently for each staircase component in all three directions) and the rotation in x–y-plane. In addition, the staircase can be made left or right handed. Figure 60 illustrates some possible variations of the staircase.

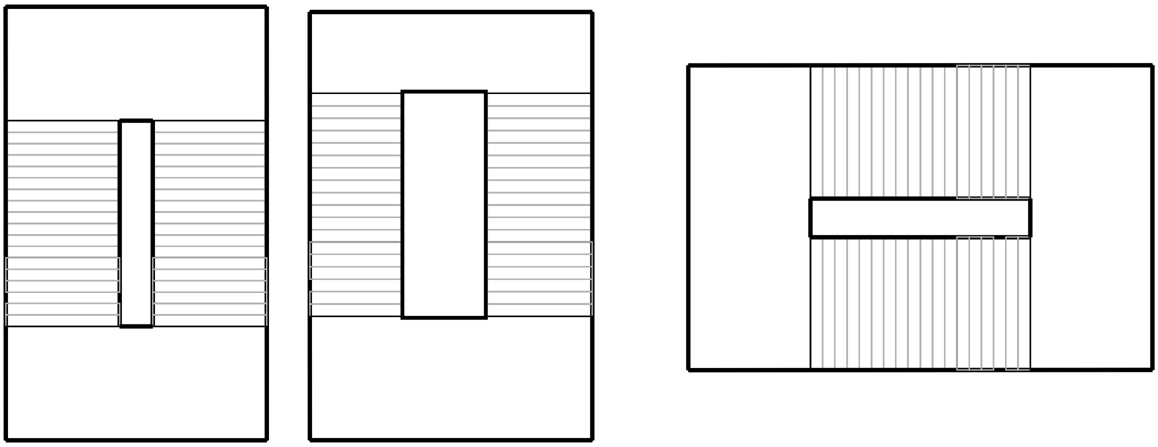


Figure 60. Geometrical variations of the staircase.

The inclusion of crowd dynamics (O3) is handled in the usual manner by using the Helbing's model for agent movement. This model includes the motive, social and wall forces. To enable the agent to exit the staircase through a door or an exit, the wall force is turned off when the agent is close to the door. An example of agents moving on the stairs is shown in Figure 61.

The computational efficiency of the crowd dynamics computations is achieved by two means:

- The human-human forces are limited between those agents that are on the same landing/stair or one node above/below. For example, an agent standing on a landing would feel the repulsion forces from other agents that are on the very same landing or the preceding and following stairs. This is extremely important because the other agents on above or below landings would otherwise be accounted for.
- The direction fields on stairs and landings are *not* computed using the flow solver as is the case on regular evacuation meshes. Instead, fixed direction fields pointing towards the next "node" are used. After some experimenting, the direction fields were construed of rectangular sections that have only one direction on the stair parts, point to the other end of the landing for those agents arriving from a stair node to a landing, and point towards the next stair node for those agents approaching the stair. This approach is illustrated in Figure 62. This approach is very efficient because the same direction fields can be applied for all parts of the stairs despite their geometrical differences.

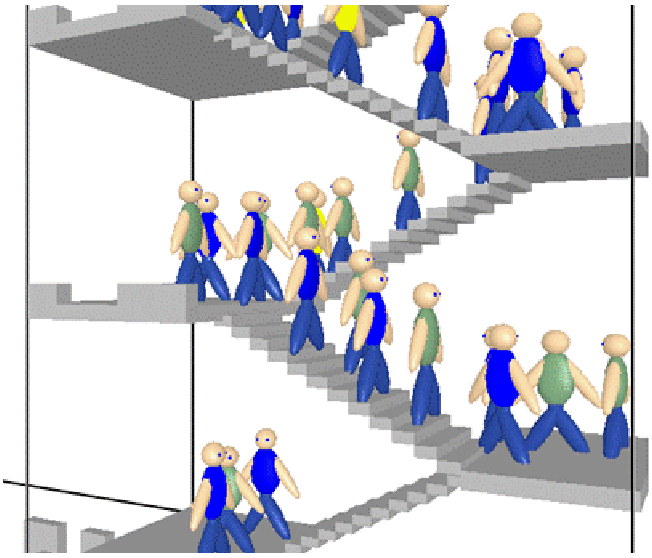


Figure 61. An example of agents moving on the stairs.

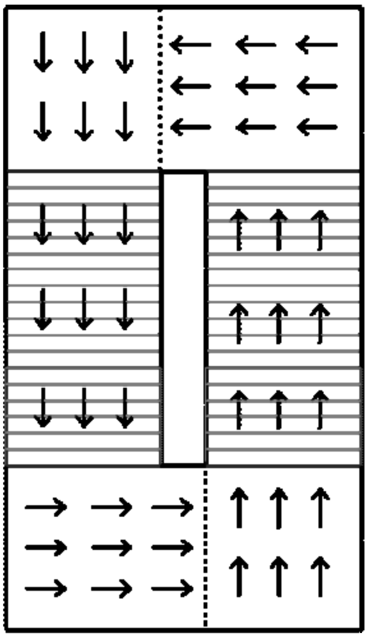


Figure 62. Fixed direction fields on the landings and stairs.

The features related to the fire and smoke effects within the staircase (O4) have not been implemented yet. The current plan is to save the toxicity and smoke conditions at one point for each node of the staircase, and apply these conditions to all agents of that particular node.

5.2.3 Limitations

The assumptions and simplifications imply the following limitations for the STRS model:

- The geometries are limited to the rectangular ones with straight sections of stairs and landings.
- The first and last node is always a landing.

The development of the STRS staircase model is still under way. Features that still wait to be implemented cause the following limitations:

- The agents inside the stairs do not feel the smoke or heat. (Expected to be fixed within 2009.)
- The group behaviour has not been tested.
- The game-theoretic door selection has not been tested in staircases.
- The geometrical objects are only two-dimensional. This means that the obstacles limiting the space are the same on all heights of the staircase. (Expected to be fixed within 2009.)
- Initially, the staircase cannot contain any humans.

5.2.4 Staircase model results

5.2.4.1 Verification tests

Four different verification tests were performed. Each of them consists of a single staircase connected to small corridors. The people are initially located inside the corridors, and the exits from the system are placed in the end of the corridors.

Flow up

In this test, three groups of type ‘Adult’ are placed on the three lowest floors. The only exit is on the top floor which must be detected automatically by the agents entering the staircase. Snapshots of the simulation are shown in Figure 63. In the end, all the agents have reached the exit.

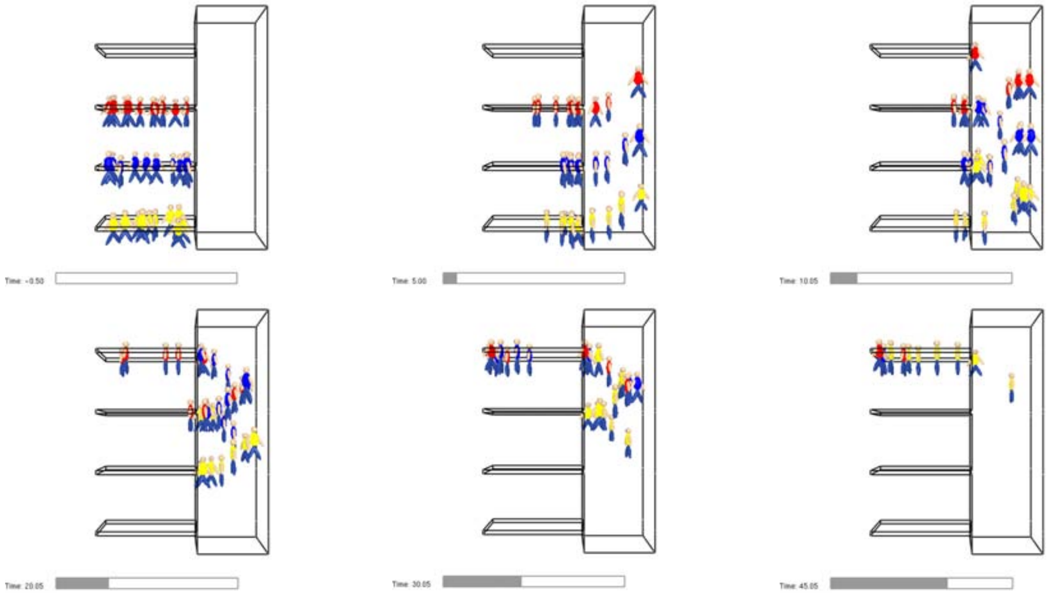


Figure 63. Snapshots of the “Flow up” verification test.

Flow up at two speeds

In this test, a group consisting of ‘Adult’ group members is placed on the lowest floor and a group of ‘Elderly’ type people on the third floor. All the agents must automatically detect the only exit that is placed on the top floor.

Snapshots of the simulation are shown in Figure 64. All the agents find their way out and the faster agents are able to pass some of the slower ones inside the staircase, thus indicating that the movement model works correctly.

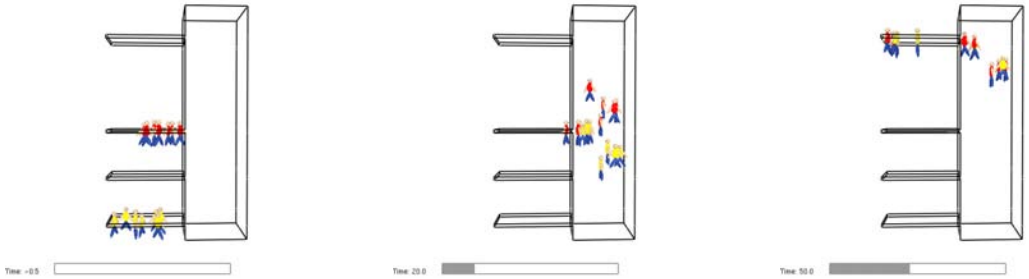


Figure 64. Snapshots of the “Flow up at two speeds” verification test.

Flow down

In this test, four groups of people are placed on the third, fourth and fifth floor. There are exits on both the first and second floors. The red, yellow and blue people are supposed to detect the exit automatically. The gray people are enforced to choose the first floor exit.

The simulation revealed that all the red, yellow and blue people left the building through the second floor, and the gray people left the building through the first floor, as illustrated by Figure 65.

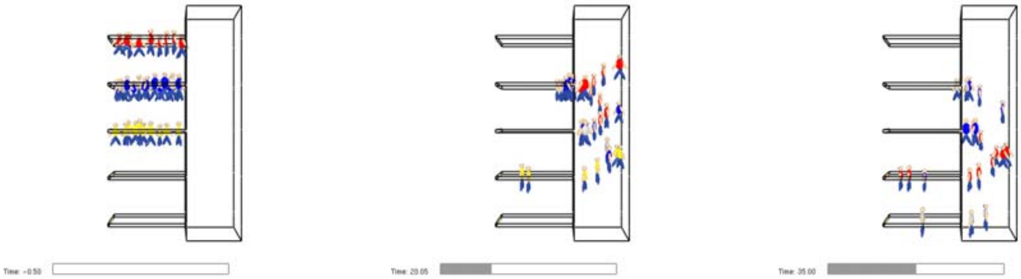


Figure 65. Snapshots of the “Flow down” verification test.

Flow to the middle

Two features in particular are tested: the automatic target detection and the effect of the direction dependent walking speeds. The simulation showed that all the agents found their way to the exit at the middle floor. Also, as shown by Figure 66, the red agents walking downwards reached the exit floor sooner than the blue and yellow agents walking upwards.

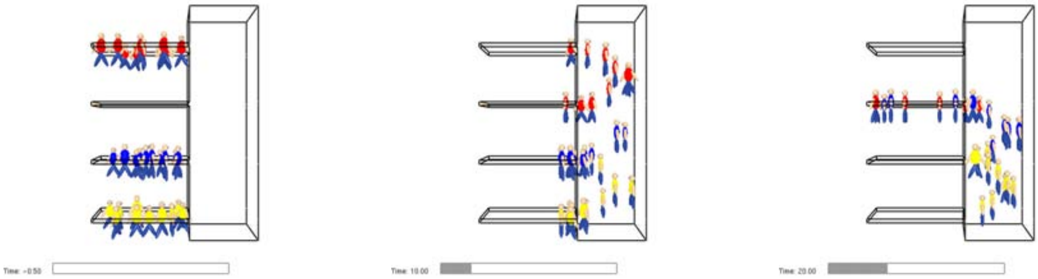


Figure 66. Snapshots of the “Flow to the middle” verification test.

5.2.4.2 Validation test

For the validation purposes, an evacuation experiment of a six-storey office building was modelled. Experimental data was collected by the VTT researchers during an evacuation drill organized by the building safety organization, and reported in [64]. The alarm was given by the sound signal (fire bell) and the efficient evacuation was ensured by the safety teams going through the offices. In the experiment, the human flows into the staircase and out of the exit door were monitored by video cameras.

The simulation model contained the staircase, entry doors on the landings, entry doors on the ground floor and the corridor on the ground floor. A snapshot of the evacuation is shown in Figure 67. The detailed entry timings were used to define accurate input boundary conditions.

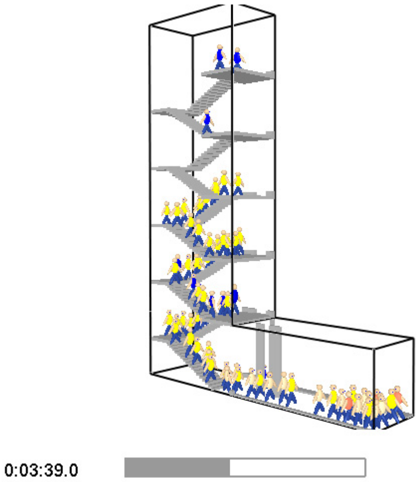


Figure 67. Snapshot of the office stair evacuation simulation.

The simulations were performed at different values for the walking speed reduction. The same values were used for all three factors: `FAC_V0_DOWN, FAC_V0_UP, FAC_V0_HORI`. Figure 68 shows the experimental and simulated result for the cumulative number of people leaving the building through the staircase exit. First people leave the door approximately one minute from the alarm. Between two and five minutes the people flow out of the door at roughly a constant rate. In fact, at least part of the time the flow was limited by the exit door capacity rather than the staircase itself. In the end, about 280 people have left the building. The results show that using the velocity factor of 0.7 leads to the best agreement between the simulation and test. The fact that the faster staircase velocity did not result in much faster evacuation was due to the limiting capacity of the exit door. Multiplying the velocities by 0.5 would lead to slightly slower evacuation than what was found in the experiment.

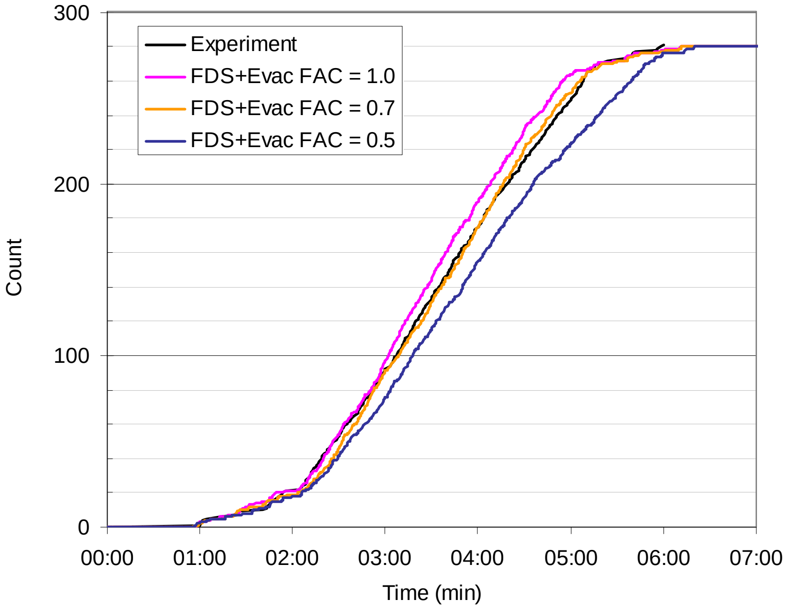


Figure 68. Comparison of the measured and simulated number of people leaving the office staircase.

6. Influence of project results on IMO rules and their development

One main task in the SURSHIP research program is to provide a possibility for researchers to come forward with ideas or suggestions for improvements of the existing safety regulations. The influence of research results on IMO rules and their development is emphasised in the SURSHIP projects.

All subprojects of SURSHIP-FIRE can have influence on IMO rule-making directly or indirectly. The possible issues are summarized below. The issues and proposals to be forwarded to IMO will be discussed and selected with the Finnish Maritime Administration.

6.1 Materials

In Subproject I – Materials, basic fire test data on materials and products have been collected and input into a database. This work can have indirect influence on IMO rules through the use of the data in Subprojects II – Hazards and III – Structures as well as in further research. Furthermore, guidelines for using test data as input of simulations can influence on issues related to alternative design.

6.2 Hazards

Subproject II – Hazards has provided practical guidelines for alternative design. For instance, methods to estimate cabin fire load and to define parameterised design fires have been presented. In addition, a methodology for alternative design of different premises on board has been created. These guidelines may have an influence on rules concerning alternative design.

6.3 Structures

In Subproject III – Structures, critical fire situations for structures have been identified. Engine room fire below a car deck has been thoroughly analysed in this project. Other critical issues brought out in a questionnaire conducted within SURSHIP cooperation include

- oxygen controlled fire in a cargo vessel, container ship or tanker, especially in the middle part

- ro-ro spaces of ro-ro and ro-pax ships when unladen (drying problems)
- prow of ships of non-metallic structure
- aluminium and composite structures.

These subjects may bring about issues for IMO rule-making.

6.4 Evacuation

Based on the query of the most important ship evacuation features, and the experiences during the development of FDS+Evac code since 2006, we have the following comments on the document: IMO MSC.1/Circ.1238, 30 October 2007 [58].

General comments

The guidelines are written from the perspective of purely stochastic treatment of evacuees' decisions. This ensures consistency between the results using different evacuation programmes but has some obvious drawbacks, such as:

- The simulation results consider mostly the physical capacity of the exit routes, but not the efficiency of the whole evacuation process.
- The coupling between the surrounding conditions and evacuees' decisions is missing. For example, the effects of fire and smoke cannot be taken into account.
- The progress of the evacuation event does not affect the decisions. For example, evacuees do not change their routes in case of observed congestion.

Based on the current information, it is impossible to tell if the purely stochastic approach will generally lead to designs that are more or less safe than what could be obtained with models considering the aspects of evacuee's decision making. However, the guidelines should consider the use of psychological decision making models as an alternative to the assumed stochastic behaviours.

An essential part of ship evacuation is the use of staircases and movement of evacuees between decks. The verification tests of ANNEX 3 do not test the software's capability to simulate these aspects.

An additional verification test should test the software's capability to

- assign humans to a staircase
- simulate movement inside the staircase
- simulate merging flows at landings, and
- to make people leave the staircase at correct deck (floor).

Specific comments

Comment 1: Annex 2, Page 4

3.7.1 Congestion within regions is identified by local population densities exceeding 4 p/m^2 for significant periods of time. These levels of congestion may or may not be significant to the overall assembly process.

Comment: Some modelling programmes do not permit high densities. E.g., if a cellular automate with a computational mesh of 0.5 m × 0.5 m is used, then the maximum density can never exceed 4.0 p/m^2. Therefore, the limiting population density should be relative to the maximum density achievable by the program, or the capability to simulate such densities should be required (possible addition to Annex 3).

Comment 2: Annex 2, Appendix, Page 5

1.6 The time difference between the actions of any two persons in the simulation should be not more than one second of simulated time, e.g. all persons proceed with their action in one second (a parallel update is necessary).

Comment: One should explain what is meant by “the actions of any two persons”. Is this the maximum time step for the movement algorithm, or is it the lowest frequency (once per second) at which rate the persons make decisions using some kind of “artificial intelligence” style decision making.

The one second time difference applies only to the models where the time is discretized. For continuous space and time models this does not apply, there one can not speak about parallel or sequential update. In some continuous space and time models one is solving a system of coupled ordinary differential equations and there the whole coupled system is solved by some algorithm for the movement of the persons. For the decision making process, the time step may be different from the one used for the movement algorithm, where the time step is usually much smaller than one second. For cellular automata -type programmes, the one second time difference could apply. Same is true for the term “parallel update”, which is a specific term of the cellular automata -type programmes.

Comment 3: Annex 2, Appendix, Page 7

3.2.2 Response time

Comment: The graphs of the distributions presented in Eqs 3.2.2.1 and 3.2.2.2 should be added to the document to reduce the risk of typing errors.

Comment 4: Annex 2, Appendix, Page 9

Table 3.5 – Walking speed on stairs

Comment: Instead of giving the min-max values, it would be better to indicate how much slower the individuals are going to walk in stairs, compared to horizontal movement. The numbers could be as percent of horizontal walking speed. A slow person on a horizontal will most probably be slow in stairs as well. The stair speeds should not be independent of the other human properties.

Example: Males older than 50 years
Stairs down: 0.60 x v_hori
Stairs up: 0.45 x v_hori

Comment 5: Annex 2, Appendix, Page 10

> *4.1.1 50 % should be initially located in service spaces and behave as passengers having walking speed and reaction time as specified in paragraph 3.*

This should explicitly specify whether to use passengers' or crew's walking speeds, as is done at paragraph 4.2.1

Comment 6: Annex 2, Appendix, Page 11

> *5.3 "...analysed should be 50 rather than 10…": Should this be the other way around, i.e., "...analysed could be 10 rather than 50..."*

Comment: This applies to the stochastic movement algorithms. If the algorithm is deterministic, then one calculation per one randomly generated population is enough. There is no need to do exactly the same calculation ten times. Another option is to use 50 different random populations for the deterministic models.

7. Summary of the results of the project

The application of sophisticated simulation and risk analysis methods in fire safety design of ships has been studied in the SURSHIP-FIRE project. The results enable wide use of new fire safety concepts in the alternative design and arrangements in fire safety.

As a result of Subproject I – Materials, fire test data of some products commonly used in shipbuilding have been stored to a free-of-charge accessible database for the use of design engineers. Guidelines have been defined for using fire test data in simulation and product development.

In Subproject II – Hazards, quantitative risk analyses of ship fire safety have been performed. In the risk-based specification of cabin fires in passenger ships, the probability of the fire to spread outside the cabin of origin has been determined, and the effectiveness of various measures for improving fire safety have been evaluated. The risk-based modelling of a cabin area has produced F-N curves revealing how often certain numbers of people are threatened due to a fire in the cabin area. These studies define procedures for analysing fire safety of cabins and cabin areas, applicable also to other cases with different features and details. Furthermore, a methodology for defining design fires for various ship spaces has been formulated and applied to shops on board as a practical example.

Subproject III – Structures has mainly concentrated on the effects of engine room fires on car deck structures. Thermal and mechanical analyses of the structures with different dimensions and insulation extents have been performed considering both the standard fire curve and the hydrocarbon curve. The results showed clearly the need for total insulation of critical sections.

A survey of specific features of ship evacuation was carried out in Subproject IV – Evacuation. Since the use of staircases and the movement of evacuees between decks is an essential part of ship evacuation, a new staircase sub-model for the FDS+Evac program was created, verified and validated. The new staircase sub-model facilitates significantly the description of complex staircases in egress simulation.

The influence of research results on IMO rules and their development is emphasised in the SURSHIP projects. The input of the SURSHIP-FIRE project on IMO rule-making can be summarized as follows. The collected basic fire test data on ship materials and products can have an indirect influence on IMO rules through studies related to fire risks of various ship spaces and structures. Guidelines for using test data as input of simulations have been defined, providing tools for alternative design. The quantitative risk analyses performed and the methodology for estimation of design fires created give practical guidelines for alternative design. Fire situations identified critical for ship structures may bring about issues for IMO rule-making. As a result of the determination of the specific features of ship evacuation and the experiences during the development of the evacuation simulation program, several general and specific comments on the IMO guidelines for evacuation analyses have been given.

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Appendix A: Tabulated fire statistics and frequencies

Table A1. Fire frequency per ship-year, as summarized in [a)].

Type of accident	**Fire frequency (per ship-year)**	**Reference period**	**Number of events**	**Number of ship-years**	**Source, category of ship, IAEA reference**
All fires	1.4×10^{-2}	1990–1996	115	8447	MAIB, UK registered merchant ships > 100 GT, (CEPN-IPSN) [b)]
All fires	1.6×10^{-2}	1981–1990	323	21 225	MAIB, UK registered merchant ships and RoRos > 100 GT, (SRD) [c)]
All fires on RoRo ferries	6.7×10^{-2} 40 % machine rooms	1989–1992	33	496	MAIB, UK RoRo ferries [d)]
Serious fires*	2.6×10^{-3}	1984–1993	859	324 220	Lloyd's, world fleet ships > 500 GT, (SRD) [e)]
Specified engine room fires**	2.9×10^{-4}	1984–1993	93	324 220	Lloyd's, world fleet ships > 500 GT, (SRD)[e)]
Serious fires	1.71×10^{-3}	1990–1995	152	88 920	Lloyd's, world, general cargo ships > 500 DWT, (JNC) [f)]
Total loss	1.1×10^{-3}	1978–1988	317	287 675	Bureau Véritas, world, – general cargo, containers and RoRo passenger ships (CEPN-IPSN) [b)]
Total loss	3.1×10^{-4}	1994–1997	55	177 418	Lloyd's, world merchant ships > 100 GT (CEPN-IPSN) [b)]

* Excluding oil tankers and liquefied gas carriers.

** Engine room fires which spread to the cargo area, or fires of a serious nature arising in the cargo hold.

[a)] IAEA. Severity, probability and risk of accidents during maritime transport of radioactive material. Final report of a co-ordinated research project 1995–1999. IAEA-TECDOC-1231. IAEA, Vienna, 2001, 188 p. ISSN 1011–4289.

[b)] Schneider, T., Armingaud, F., Tabarre, M. Statistical Analysis of Accident Data Associated with Sea Transport (Data from 1994–1997), Rep. CEPN-IPSN, NTE/99/02, Institut de Protection et de Sûreté Nucléaire, Fontenay-aux-Roses (1999).

[c)] Selway, M., Smith, F.M., Bickley, A.M. The Frequency of a Severe Fire on the Freight Ferry "Nord Pas-de-Calais". AEA Technology, Safety and Reliability Directorate, Rep. SRD/22459/NTL/001, Atomic Energy Authority, Risley (1991).

[d)] Lange, F. et al. Evaluation of the Safety of Vitrified High Level Waste Shipments from UK to Continental Europe by Sea, Rep. CEC Project 4.1020/D/96-001, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS), Cologne (1998).

[e)] Kay, D., Woodward, P.E., Zahid, M. Assessment of frequency of fire on a ship carrying irradiated nuclear fuel, AEA Technology, Consultancy Services, AEA/CS/16401249/ZJ/1577/001, Atomic Energy Authority, Risley (1995).

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Table A2. Total loss fire frequency per ship type as summarized in [g)].

Ship type	**Fire frequency / ship type / year Lloyd's, 1994–1997**	**Fire frequency / ship type / year Bureau Véritas, 1978–1988**
General cargo	2.6×10^{-4}	1.2×10^{-3}
Passenger / general cargo	No event	Not specified
Container	4.0×10^{-4}	5.3×10^{-4}
Ro-Ro cargo	2.95×10^{-4}	Not specified
Passenger / Ro-Ro cargo	5.4×10^{-4}	6.6×10^{-4}
Passenger	5.7×10^{-4}	Not specified
Overall total loss fire frequency for the above mentioned ship types	3.2×10^{-4}	

[g)] IAEA. Severity, probability and risk of accidents during maritime transport of radioactive material. Final report of a co-ordinated research project 1995–1999. IAEA-TECDOC-1231. IAEA, Vienna, 2001, 188 p. ISSN 1011–4289.

Table A3. Frequency of serious fires and fatalities due to fire as reported in [h)]. Data from Lloyd's register – Fairplay.

Ship type	**Serious fire frequency per ship-year**	**Fatality frequency per ship-year**	**Reference period**	**Number of events**	**Number of ship-years**
RoPax > 5000 GRT	1.9×10^{-3}	1.3×10^{-4}	1990–2002	59	30232
Cruise liner > 4000 GRT	1.2×10^{-2}	7.7×10^{-4}	1990–2002	37	3185

[h)] Vanem E. & Skjong R. Fire and evacuation risk assessment for passenger ships. INTERFLAM 2004: Proceedings of the 10th international fire science & engineering conference, Edinburgh, Scotland, 5–7 July 2004. Vol 1. Interscience Communications Ltd., London, 2004. Pp. 365–374.

Table A4. Fire frequency per ship type as reported in [i]. Data from DNV during 1992–2004, 300 reported fire incidents, more than 25 000 ship-years.

Ship type	**Fire frequency per ship-year**
Whole DNV fleet, 4300 vessels	7×10^{-3}
Oil carriers	2×10^{-3}
Fishing vessels	2×10^{-3}
Supply vessels	2×10^{-3}
Dry cargo	3×10^{-3}
OBO	4×10^{-3}
Bulk	4×10^{-3}
Chemical carriers	6×10^{-3}
RoRo, container	7×10^{-3}
Gas carriers	7×10^{-3}
Passenger	1.6×10^{-2}

[i] Nilsen, D. Engine room fire safety. Statistics, details and measures. DNV‘s traditional autumn shipping seminar, Riga, 14.11.2007. 34 transparencies. http://www.dnv.lv/juras_lietas/autumn_shipping_seminar.asp. Referred to 28.2.2008.

Table A5. Fire frequency per ship-year as presented in [j]. Data from Lloyd’s casualty database (LMIS).

Ship type	**Serious fire frequency**	**Total loss frequency due to fire**	**Reference period**	**Number of fire events**	**Number of ship-years**
RoPax in NW Europe > 1000 GRT	1.0×10^{-2}	No event	1978–1994	36	3 485
RoPax worldwide	4.6×10^{-3}	9.0×10^{-4}	1978–1987	255 (18 total losses)	10 000

[j] Spouge, J. Safety Assessment of Passenger Ro-Ro vessels. Methodology Report for the North West European Project on Safety of Passenger/Ro-Ro vessels. DNV Technical Report C6185, 1996. 59 p. + app. 373 p.

Table A6. Fire frequency per ship-year for UK ships over 100 GRT as presented in [k].

Type of accident	**Fire frequency per ship-year**	**Reference period and reference**
Minor casualties (incl. serious casualties)	1.4×10^{-2}	1979–1988 [l]
Serious casualties (including total losses)	1.2×10^{-3}	1979–1988 [l]
Total losses	2.1×10^{-4}	1979–1988 [l]
Incidents	1.8×10^{-2}	1990–1995 [m]
Total losses	1.3×10^{-4}	1990–1995 [m]

[k] Spouge, J. Safety Assessment of Passenger Ro-Ro vessels. Methodology Report for the North West European Project on Safety of Passenger/Ro-Ro vessels. DNV Technical Report C6185, 1996. 59 p. + app. 373 p.

[l] DoT. Casualties to vessels and accidents to men, return for 1988. Department of Transport, HMSO, 1989.

[m] MAIB. Annual report 1994. Marine Accident Investigation Branch, Department of Transport, HMSO, 1995.

Table A7. Frequency of fatalities due to fire as reported in [n)]. Data from Lloyd's Marine Intelligence Unit (LMIU) ship characteristics and casualty database.

Ship type	**Fatality frequency per ship-year**	**Reference period**	**Number of events**	**Number of ship-years**
Passenger	2.49×10^{-3}	1978–1995	223	89 575

[n)] Kaneko, F. Methods for probabilistic safety assessments of ships. J Mar Sci Technol. Vol 7, No. 1, 2002, pp. 1–16.

Table A8. Origin of the fire as summarized in [o)].

Origin of the fire*	**Bureau Véritas (CEPN-IPSN) 1978–1988**	**Lloyd's (CEPN-IPSN) 1994–1997**	**MAIB-CVAM (SRD) 1981–1990**
Machinery room	64 %	61 %	40 %
Quarters	39 %	16 %	Not defined
Holds	8 %	3 %	Not defined

* Fires can originate in more than one area (in which case, the total would exceed 100 %).

[o)] IAEA. Severity, probability and risk of accidents during maritime transport of radioactive material. Final report of a co-ordinated research project 1995–1999. IAEA-TECDOC-1231. IAEA, Vienna, 2001. 188 p. ISSN 1011–4289.

Table A9. Origin of the fire at passenger ships as reported in [p)]. Data from Lloyd's register – Fairplay.

Origin of the fire*	**RoPax**		**Cruise liners**	
	Number (%)	Fire frequency per ship-year	Number (%)	Fire frequency per ship-year
Engine room	61.0	1.2×10^{-3}	67.6	8.1×10^{-3}
Car deck	8.5	1.6×10^{-4}	Not specified	
Store room/laundry	Not specified		13.5	1.6×10^{-3}
Accommodation area	8.5	1.6×10^{-4}	8.1	9.7×10^{-4}
Public spaces	10.2	1.9×10^{-4}	Not specified	
Others/unknown	11.9	2.3×10^{-4}	10.8	1.3×10^{-3}

* Fires can originate in more than one area (in which case, the total would exceed 100 %).

[p)] Vanem E. & Skjong R. Fire and evacuation risk assessment for passenger ships. INTERFLAM 2004: Proceedings of the 10th international fire science & engineering conference, Edinburgh, Scotland, 5–7 July 2004. Vol. 1. Interscience Communications Ltd., London, 2004. Pp. 365–374.

Table A10. Origin of the fire according to DNV statistics 1992–2004 q).

Origin of fire	**Number (%)**	**Fire frequency per ship-year**
Engine room	63	4.4×10^{-3}
Accommodation	10	7.0×10^{-4}
Cargo area	27	1.9×10^{-3}

q) Nilsen, D. Engine room fire safety. Statistics, details and measures. DNV‘s traditional autumn shipping seminar, Riga, 14.11.2007. 34 transparencies. http://www.dnv.lv/juras_lietas/autumn_shipping_seminar.asp. Referred to 28.2.2008.

Table A11. Origin of the fire on RoPax vessels in north-west Europe as presented in r). Data from Lloyd’s casualty database (LMIS).

Origin of fire	**Number of events**	**Fire frequency per ship year**
Machinery spaces		7.2×10^{-3}
Main engine room	18	5.2×10^{-3}
Auxiliary engine room	3	8.6×10^{-4}
Switchboard	4	1.1×10^{-3}
Boiler room	1	2.9×10^{-4}
Vehicle deck		8.0×10^{-4}
Vehicles	2	5.7×10^{-4}
Garbage store	1	2.9×10^{-4}
Accommodation		2.0×10^{-3}
Cabins	4	1.1×10^{-3}
Restaurant/galley	2	5.7×10^{-4}
Linen store	1	2.9×10^{-4}
Total	36	1.0×10^{-2}

r) Spouge, J. Safety Assessment of Passenger Ro-Ro vessels. Methodology Report for the North West European Project on Safety of Passenger/Ro-Ro vessels. DNV Technical Report C6185, 1996. 59 p. + app. 373 p.

Table A12. Origin of fire as presented in s).

Origin of the fire	**Fire frequency per ship year**
Machinery room	9.3×10^{-4}
Accommodation	1.4×10^{-4}
Cargo spaces	2.0×10^{-4}
All spaces	1.3×10^{-3}
Specifications	
Type of ship	Passenger ships
Database and source	IMO GISIS
Reference period	1998–2007
Fire casualties	80

s) Karhula, T. Matkustajalaivan hyttipalon riskiperustainen määrittäminen [Risk Based Specification of Cabin Fire in Passenger Ships]. Master’s Thesis. Helsinki University of Technology, 2008. 106 p. (In Finnish.)

Table A13. Fire frequency per ship nautical mile sailed or port call as summarized in [t)].

Type of fire	**Fire frequency**	**Reference period**	**Source**
All fires	Non-port: 9.6×10^{-8} per nmi Port: 5.4×10^{-5} per port call	1979–1993	Lloyd's, (SNL) [u)]
Serious fires	2.85×10^{-8} per nmi	1990–1995	Lloyd's, (JNC)
Total loss	General cargo: 5×10^{-9} per nmi Container: 3.1×10^{-9} per nmi Ro-Ro: 2.8×10^{-9} per nmi	1978–1988	Bureau Véritas, (CEPN-IPSN)

[t)] IAEA. Severity, probability and risk of accidents during maritime transport of radioactive material. Final report of a co-ordinated research project 1995–1999. IAEA-TECDOC-1231. IAEA, Vienna, 2001. 188 p. ISSN 1011–4289.

[u)] Ammerman, D.J., Koski, J.A., Sprung, J., SeaRAM: A U.S. DOE Study of Maritime Risk Assessment Data and Methods of Analysis, Sandia National Laboratories, Albuquerque, NM (1988).

Table A14. Location of the ship when fire originated (% of all fires) as summarized in [v)].

Location of the ship	**Bureau Véritas (CEPN-IPSN) 1978–1988**	**Lloyd's (SNL) 1979–1993**	**Lloyd's (SRD) 1984–1993**
Port fires	43.4 %	38.2 %	37.6 %
Non-port fires	56.6 %	61.8 %	62.4 %

[v)] IAEA. Severity, probability and risk of accidents during maritime transport of radioactive material. Final report of a co-ordinated research project 1995–1999. IAEA-TECDOC-1231. IAEA, Vienna, 2001. 188 p. ISSN 1011–4289.

Table A15. Time required to extinguish fires for all ships as summarized in [w)].

Time to extinguish	**At port (%)**	**Under way (%)**
0–30 min	20	18
+30 min–2 hr	31	28
+ 2 hr–10 hr	29	28
+ 10 hr–1 day	9	15
more then one day	11	11
Specifications:		
Type of ship	World fleet (reported to IMO) + UK registered RoRos and ferries	
Database and source	IMO + MAIB (SRD) [x)]	
Reference period	1962–1989	
Fire casualties	382	

[w)] IAEA. Severity, probability and risk of accidents during maritime transport of radioactive material. Final report of a co-ordinated research project 1995–1999. IAEA-TECDOC-1231. IAEA, Vienna, 2001. 188 p. ISSN 1011–4289.

[x)] Selway, M., A Study of Typical Times for the Duration of a Ship Fire, AEA Technology, Safety and Reliability Directorate, Rep. SRD/4045/NTL/002, Atomic Energy Authority, Risley (1992).

Table A16. Selected building fire frequencies based on Finnish PRONTO database [y)], London Fire Brigade's Real Fire Library [z)] and Swiss GVB [aa)].

Building category	**Finland 1996–2001** **Building fire frequency (1/building-year)**	**London 1996–1999** **Building fire frequency (1/building-year)**	**Berne, Switzerland 1986–1995** **Building fire frequency (1/building-year)**
Dwelling	1.3×10^{-3}	Excluded from the study	
Shop, hotel, restaurant	3.2×10^{-3}		
Hotel, boarding house etc.		6.7×10^{-2}	
Shop, restaurant, public house, supermarket etc.		3.0×10^{-3}	
Industrial building and warehouse	1.4×10^{-2}	3.5×10^{-3}	
Office	3.8×10^{-3}	1.7×10^{-3}	
All buildings	2.5×10^{-3}	3.8×10^{-3}	1.2×10^{-2}
	Building fire frequency ($1/m^2$-year)	Building fire frequency ($1/m^2$-year)	Building fire frequency ($1/m^2$-year)
Dwellings	6.3×10^{-6}		3.3×10^{-5}
Industrial building and warehouse	1.1×10^{-5}	6.9×10^{-6}	
Industrial	9.6×10^{-6}		1.1×10^{-5}
Shop and commercial	6.6×10^{-6}	2.2×10^{-5}	
Office	2.5×10^{-6}	5.3×10^{-6}	
Public and office	4.7×10^{-6}		1.1×10^{-5}
All buildings	9.0×10^{-6}		3.2×10^{-5}

[y)] Tillander, K. Utilisation of statistics to assess fire risks in buildings. Espoo, VTT Building and Transport, 2004. VTT Publications 537. 224 p. + app. 37 p.

[z)] Holborn, P.G., Nolan, P.F., Golt, J. & Townsend, N. Fires in workplace premises: risk data. Fire Safety Journal, Vol. 37, 2002, p. 303–327.

[aa)] Fontana, M. Favre, J.P. & Fetz, C. A survey of 40,000 building fires in Switzerland. Fire Safety Journal, Vol. 32, 1999, p. 137–158.

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Author(s)
Tuula Hakkarainen, Jukka Hietaniemi, Simo Hostikka, Teemu Karhula, Terhi Kling, Johan Mangs, Esko Mikkola & Tuuli Oksanen

Title

Survivability for ships in case of fire

Final report of SURSHIP-FIRE project

Abstract

Survivability of ships in case of fire has been studied in the SURSHIP-FIRE research project as a part of the SURSHIP cooperation, a coordinated European research program on Maritime safety. The work was performed in four subprojects related to materials used in shipbuilding, fire hazards on board, ship structures, and evacuation in ship conditions.

Fire test data of products commonly used in shipbuilding were stored to a free-of-charge accessible database for the use of design engineers. Guidelines were defined for using fire test data in simulation and product development.

Procedures for quantitative fire risk analyses of cabins and cabin areas were defined, applicable also to other cases with different features and details. A methodology for defining design fires for various ship spaces was formulated and applied to shops on board as a practical example. The sophisticated simulation and risk analysis tools utilized in the work were the FDS5 fire simulation program with its evacuation module FDS+Evac, the Probabilistic Fire Simulator, and the method of time-dependent event trees.

The effects of engine room fires on car deck structures were analysed in detail since the situation was recognised critical for the structural integrity of the ship. Thermal and mechanical analyses of the structures with different dimensions and insulation extents were performed considering both the standard fire curve and the hydrocarbon curve.

A survey of specific features of ship evacuation was carried out. Since the use of staircases and the movement of evacuees between decks is an essential part of ship evacuation, a new staircase sub-model for the FDS+Evac program was created, verified and validated.

The results of the SURSHIP-FIRE project can influence on IMO rules for alternative fire safety design of ships. The contributions of SURSHIP-FIRE are guidelines for using fire test data as input of simulations, a methodology for estimation of design fires, practices for quantitative risk analyses, a summary of critical fire situations for structures, and suggested improvements of the IMO guidelines for evacuation analyses.

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Tekijä(t)
Tuula Hakkarainen, Jukka Hietaniemi, Simo Hostikka, Teemu Karhula, Terhi Kling, Johan Mangs, Esko Mikkola & Tuuli Oksanen

Nimeke

Laivojen selviytymiskyky tulipalossa
SURSHIP-FIRE-projektin loppuraportti

Tiivistelmä

Laivojen selviytymiskykyä tulipalossa tutkittiin SURSHIP-FIRE-projektissa osana eurooppalaista meriturvallisuuden SURSHIP-tutkimusohjelmaa. Työn neljä osatehtävää liittyivät laivanrakennuksessa käytettäviin materiaaleihin, tulipaloriskeihin laivoilla, laivojen rakenteisiin ja poistumiseen laivaolosuhteissa.

Laivanrakennuksessa yleisesti käytettyjen tuotteiden palokoetuloksia tallennettiin maksuttomaan tietokantaan suunnittelijoiden käytettäviksi. Palokoetulosten käytölle simuloinnissa ja tuotekehityksessä laadittiin ohjeistus.

Hyttien ja hyttialueiden kvantitatiiviseen riskianalyysiin kehitettiin menettelytapoja, jotka ovat sovellettavissa ominaispiirteiltään erilaisten tapausten tarkasteluun. Mitoituspalojen määrittelyyn laivan eri tiloissa luotiin metodologia, jota sovellettiin laivan myymälätiloihin.

Konehuonepalon vaikutuksia autokannen rakenteisiin tutkittiin termisin ja mekaanisin analyysein. Rakenteita eri mittasuhtein ja eristyslaajuuksin tarkasteltiin sekä standardi- että hiilivetypalokäyrän mukaisessa palorasituksessa.

Laivan poistumistilanteille ominaiset piirteet kartoitettiin. Koska portaikkojen käyttö ja ihmisten siirtyminen laivan kannelta toiselle ovat laivoilla keskeinen osa poistumista, FDS+Evac-poistumislaskentaohjelmaan luotiin uusi validoitu portaikkomalli.

SURSHIP-FIRE-projektin tulokset voivat vaikuttaa laivojen vaihtoehtoista paloturvallisuussuunnittelua koskeviin IMO-säädöksiin. Projektin tuloksena syntyi ohjeistus palokoetulosten käytölle simuloinneissa, metodologia mitoituspalojen määritykseen, menettelytapoja kvantitatiivisiin riskianalyyseihin, rakenteille kriittisten tulipalotilanteiden yhteenveto ja kehitysehdotuksia poistumisanalyyseja koskevaan IMO:n ohjeistukseen.

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• • • VTT RESEARCH NOTES 2497 SURVIVABILITY FOR SHIPS IN CASE OF FIRE. FINAL REPORT OF SURSHIP-FIRE PROJECT

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The results of the SURSHIP-FIRE project can influence on IMO rules for alternative fire safety design of ships. The contributions of SURSHIP-FIRE are guidelines for using fire test data as input of simulations, a methodology for estimation of design fires, practices for quantitative risk analyses, a summary of critical fire situations for structures, and suggested improvements of the IMO guidelines for evacuation analyses.

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