Smoke Control Systems Aboard

- A risk analysis of smoke control systems in accommodation spaces on passenger ships

Caroline Andersson
Daniel Säterborn

Department of Fire Safety Engineering
Lund University, Sweden

Brandteknik
Lunds tekniska högskola
Lunds universitet

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Rökkontrollsystem ombord – En riskanalys av rökkontrollsystem i publika utrymmen på passagerarfartyg

Caroline Andersson
Daniel Säterborn

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Abstract: This report contains a quantitative as well as a qualitative risk analysis of smoke control system in accommodation areas aboard large passenger ships. A discussion of the current prescriptive rules in SOLAS and the introduction of performance based design is made. Finally, areas of further research are suggested. (English)

While every effort has been made to ensure that the content within this report is true and correct, errors can never be guaranteed against, so the reader should show due care in using any of the report's content.

Department of Fire Safety Engineering
Lund University
P.O. Box 118
SE-221 00 Lund
Sweden
brand@brand.lth.se
http://www.brand.lth.se/english
Telephone: +46 46 222 73 60
Fax: +46 46 222 46 12

Brandteknik
Lunds tekniska högskola
Lunds universitet
Box 118
221 00 Lund
brand@brand.lth.se
http://www.brand.lth.se
Telefon: 046 - 222 73 60
Telefax: 046 - 222 46 12

Summary
The purpose of this study is to evaluate the risk level associated with utilization of smoke control systems aboard large passenger ships.

The background of this study is the introduction of performance based design in SOLAS chapter II-2. In the present SOLAS the regulations concerning smoke control aboard ships are very simplified. Therefore, Sweden has proposed to the IMO that new regulations should be introduced concerning this area. The first matter is the regulations adapted on accommodation areas aboard ships. Hence, this report is limited to only consider accommodation areas. Other limitations are further specified in the main report.

The base for this study was the *M/S Skåne*, a Ro/Ro vessel operating in the Baltic Sea. The vessel was used as an input source for different conditions concerning geometry, interior and configurations of the existing ventilation system. *M/S Skåne's* geometries were altered to also represent more general geometries. These geometries are said to be on the fictive ship *M/S Alternative*. In many cases the input data used in the study are specific for the object. With this in mind, direct use of these data in risk analyses of other objects should not be made.

The analysis was divided into two parts; *a quantitative risk analysis* and *a qualitative risk analysis*. A total of 7 different main scenarios, each with a number of sub-scenarios, were analysed quantitatively with the computer model CFast to establish the required extraction capacities needed for a smoke control system. The results obtained were treated qualitatively by the means of using earlier research in the field as comparison and to discuss typical design solutions and risk factors. Finally conclusions were drawn and suggestions of further research given.

Complementary discussions on existing regulations and the introduction of performance based design was carried out. These discussions include the problem with setting reasonable performance criteria for the smoke free height on ships and the possibility of minimizing the fire load in the interior.

Results:
The main conclusion of this report is that a smoke control system, if correctly installed and used, improves the means of egress for the studied geometries. Pros and cons, economical risks and reliability of the system have to be individually analysed and evaluated for each object. Further conclusions drawn from the results are listed in short below:

- ***Fire in the cabin area:*** It is necessary to install a separate smoke control system in the cabin area if not a higher capacity HVAC-system can be used. The exhaust should be placed in the corridor, preferably equally distributed. Supply air should as a rule be taken from the cabins existing supply air system and from adjacent stairway enclosures. Separate smoke extraction exhausts in each cabin is not recommended.

- ***Fire in large public spaces:*** If the HVAC-system in public areas is designed to provide 12 changes/h, the system can be said have enough capacity to be used as a smoke control system. One neither needs more powerful fans or larger dimensions on the ducts since these are designed for large capacities anyway. However, additional upgrading concerning temperature resistance etc. has to be done.

- ***Fire in the arcade – small public space:*** The HVAC system installed in a public area cannot straight off be considered to have the required capacity of a purpose designed smoke control system. In contrast to the larger public spaces this typical example has a capacity that is far below the required. Hence, every system has to be designed on basis of a specific design fire. The recommended solution is to place the smoke extractions in the arcade and/or to limit the amount of fire load.

- ***Fire in the atrium:*** The existing regulations in SOLAS do not propose a reasonable solution for smoke control systems applicable to different atria structures. The applicability is limited since no consideration is taken to either the fire load or the requirement that the smoke layer should be kept at a safe level above deck in all evacuation routes, independent of their level in the atrium. The normal HVAC-system is in most of the studied cases barely sufficient and consequently it is relatively easy to upgrade it to meet the requirements of a smoke control system.

Sammanfattning
Syftet med denna arport är att utvärdera den risk som användandet av rökkontrollsystem ombord på passagerarfartyg kan innebära.

Bakgrunden till arbetet ligger i införandet av funktionsbaserad dimensionering i SOLAS. I den nuvarande SOLAS är regleringen av rökkontrollsystem på båtar väldigt förenklad. Med anledning av detta har Sverige föreslagit till IMO att nya regler ska införas inom detta område. Det första att behandla är reglerna för de publika delarna ombord. Denna rapport är därför begränsad till att enbart behandla de publika delarna. Andra begränsningar specificeras i huvudrapporten.

Till grund för analysen ligger *M/S Skåne*, en Ro/Ro färja som trafikerar Östersjön. Fartyget har använts som indata till olika geometrier, inredningar och befintliga ventilationslösningar. *M/S Skånes* geometrier har ändrats för att även kunna representera mer generella geometrier. Dessa geometrier har sagts finnas på det fiktiva skeppet *M/S Alternative*. I många fall är den indata som används i analysen specifik för objektet. Med detta i åtanke bör inte dessa indata användas i andra analyser.

Analysen utfördes i två delar; *en kvantitativ riskanalys* och *en kvalitativ riskanalys*. Totalt analyserades 7 olika huvudscenarion kvantitativt med datorprogrammet CFast. Samtliga dessa bestod av ett antal delscenarion. Analysen gjordes för att fastställa vilka extraktionskapaciteter på rökkontrollsystem som kan behövas. De erhållna resultaten behandlades sedan kvalitativt genom att tillämpa tidigare arbete inom området som jämförelse och som underlag för en diskussion kring olika systemlösningar och riskfaktorer. Slutligen drogs slutsatser och förslag på vidare forskning lades fram.

Kompletterande diskussioner kring befintliga regelverk samt kring införandet av funktionsbaserade regler har också förts. Diskussionerna innefattade problemet med att använda rimliga kriterier för brandgasfri höjd att applicera på fartyg samt möjligheten att minimera brandbelastningen från inredningen.

Resultat:
Huvudslutsatsen i rapporten är att rökkontrollsystem, om det installeras och används rätt, förbättrar utrymningsförhållandena för de geometrier som studerats. Fördelar och nackdelar, ekonomiska risker och tillförlitligheten hos systemet måste analyseras och utvärderas individuellt för varje objekt. Övriga slutsatser som dragits redovisas i sammanfattad form nedan:

- ***Brand i hyttsektioner:*** Om inte en högre kapacitet kan tas ut från det befintliga luftkonditioneringssystemet är det nödvändigt att installera ett separat rökkontrollsystem i hyttektionen. Utsugen skall placeras i korridoren, helst jämnt fördelade. Tilluften skall som regel tas från varje hytts befintliga ventilationssystem och från anslutande trapphus. Det rekommenderas inte att ha ett separata utsug för brandgasevakuering i varje hytt.

- ***Brand i stora publika utrymmen:*** Om luftkonditioneringssystemet i de publika delarna dimensioneras för att förse utrymmet med 12 luftomsättningar/timme, kan systemet anses ha tillräcklig kapacitet för att användas som rökkontrollsystem. Man behöver då varken kraftigare fläktar eller större dimensioner på rören eftersom de redan är dimensionerade för stora kapaciteter.

- ***Brand i arkaden – små publika utrymmen:*** Luftkonditioneringssystemet som är installerat i ett publikt utrymme kan inte rakt av anses ha den kapacitet som ett rökkontrollsystem kräver. I motsats till de större publika utrymmena har detta specifika exempel kapaciteter som är långt under vad som krävs. Med anledning av detta måste varje system som installeras dimensioneras för specifik dimensionerande brand. Den rekommenderade lösningen är att placera utsugen till rökkontrollsystemet i arkaden och/eller att begränsa mängden bränsle.

- ***Brand i atrier:*** De befintliga SOLAS reglerna föreslår inte någon rimlig lösning för rökkontrollsystem som kan appliceras på olika atriestrukturer. Tillämpbarheten är begränsad eftersom det inte tas någon hänsyn till varken brandbelastning eller till kravet att brandgaslagret bör hållas på en trygg nivå över golvet i alla utrymningsvägar, oberoende av våning i atriet. Luftkonditioneringen är i de flesta av de studerade fallen nästintill tillräcklig för att kunna verka som ett rökkontrollsystem. Inga större åtgärder behöver således vidtagas för att uppgradera det till att möta kraven på ett rökkontrollsystem.

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Caroline Andersson and Daniel Säterborn

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1 Introduction

1.1 Background

Chapter II-2 in SOLAS, Safety Of Life At Sea, concerning the fire safety aboard ships, has been altered a number of times over the years. The many changes and adaptations made the regulations more difficult to apply. In 1991 it was decided to make a comprehensive review of chapter II-2 with the possibility of using performance based design as an alternative to the prescriptive regulations. During this review it was discussed to include new regulations concerning smoke control on passenger ships. It was however decided that these requirements should be issued as a circular from the Maritime Safety Committee (MSC) instead, except a generalised requirement for smoke extraction in atriums.

In the present SOLAS the regulations concerning smoke control aboard ships are very simplified. Therefore, Sweden has proposed to the IMO that new regulations should be introduced concerning this area. The first matter is the regulations adapted on accommodation areas aboard ships. To formulate these regulations the Swedish Maritime Administration are interested in a scientific report focused on the risk level combined with utilization of smoke control systems aboard ships. This report shall therefore constitute a basis for the MSC circular, which is to be presented in the beginning of November 2001 to the IMO.

1.2 Purpose of the study

The purpose of this study is to evaluate the risk level associated with usage of smoke control systems aboard ships in order to provide further information to be used during the development of the MSC circular. This is to be done with a scientific report that answers the following questions:

- How could a system for smoke control be designed?
- How does a smoke control system affect the safety on board by the means of egress?
- How should the system be configured to operate most efficiently?
- To what extent is the HVAC-system of a ship sufficient to work as a smoke control system and what changes has to be made to such a system?
- Does a smoke control system imply any additional risks? In that case, what risks?
- What role does a smoke control system have in the overall fire safety system on a ship?

1.3 Methodology

Progress of the study

To begin with, extensive studies of literature in the area of fire safety aboard ships have been made. The purpose of these studies was mainly to get acquainted with the terminology and the differences between fire safety in ordinary buildings and that on ships. Literature on smoke ventilation and documents on earlier research in the field have also been studied.

The research started with a visit to the World Maritime University in Malmö, Sweden, where discussions and a brief introduction to the field were held. Visits to a typical modern Baltic train ferry, the *M/S Skåne*, was made in purpose to collect data, drawings and other important information for the report. To get a better understanding of the function and construction of systems for smoke control, a visit to *ABB - Fläkt Marine AB*, a consulting firm specialised on ventilation for maritime use, was made. These visits can also be seen as a supplement to the literature study.

To determine the need of an active smoke control system, the functional requirements of the system must be settled. This should be done with consideration of different geometries and fire scenarios in order to get a representative result for the type of vessels comprised in this study. Therefore, a hazard analysis based on the collected data was made in order to generate the different fire scenarios. However, the studied object, *M/S Skåne*, does not fully represent the range of possible variations in geometry that are becoming more and more common in modern passenger ships. This resulted in creating scenarios with alternative geometries based on the geometries of M/S Skåne.

Computer simulations (CFast) and hand calculations make out the quantitative risk analysis of different solutions for smoke control systems. For most of the scenarios sensitivity analyses have been made in order to deal with the uncertainties of parameters as input data, computer software etc.

To obtain a wider understanding of the risks associated with smoke control systems aboard ships, a study was made to qualitatively cover aspects like reliability, negative side effects and other practical problems related as well as economical consequences. A discussion of the present regulations in SOLAS and ISO-standard has also been made. Finally the possibilities of performance based design was subject for a discussion leading to questions like: What will be the result of setting a different performance criteria concerning the smoke free height? Can an insufficient smoke control system be compensated by stricter requirements concerning fire load in the accommodation areas?

Problems

The project was initiated in May 2001. Since the work partly included pioneering work, problems to find experts within the scientific topic occurred, which partly was explained by people having their summer vacation. Also, due to the pioneering work, information about specific solutions for smoke control systems has appeared to be confidential.

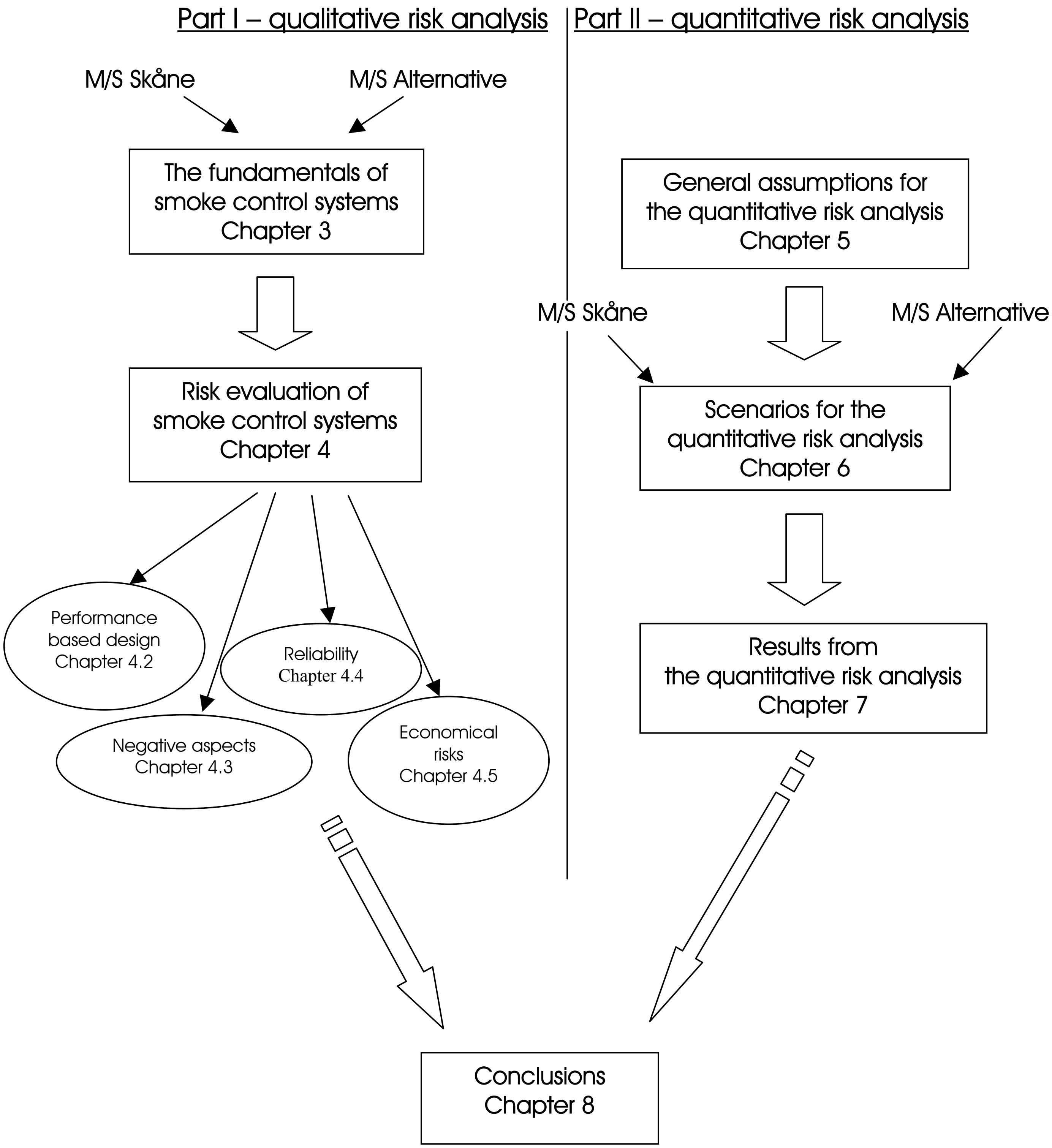
We failed getting hold of detailed statistics, needed to perform a quantitative uncertainty analysis. The statistic found was very expensive, which was why we had to settle with a qualitative discussion of the risks brought by an installation of a smoke control system.

A regression equation was derived to analyse how the smoke layer height, H_s, depends on different heat release rates, $\dot{Q}$ and ventilation capacities, $\dot{V}$. Since there has been a problem finding detailed statistic of fires aboard passenger ships, the work could not proceed from here. The thought was to perform an uncertainty analysis of the equation, giving the parameters different distributions and probabilities. The regression analysis is presented in brief in Appendix K.

All simulations have been carried out in a computer programme called CFast. This software is intricate; not very user friendly as geometries becomes more and more complex. Due to this the simulations caused us more problems than expected, since many simulations had to be restarted.

1.4 Overview of the main report

To help the readers find the specific result of interest and to give an overview of the report a short guide is presented below.



1.5 Limitations

The central limitations and assumptions made in the study are presented below. Information on more detailed assumptions made can be seen under each specific scenario.

Design Fire Scenarios
The study only comprises smoke control systems for the accommodation areas of the objects, meaning that high-risk areas like engine rooms and cargo decks will be left out. For these areas separate investigations have been or will have to be made.

In reality, the accommodation areas of the studied object *M/S Skåne* are completely protected by HI-FOG water mist sprinklers, which not all ships are. To be able to analyse the worst probable cases for a fire on a typical passenger ship, the fire suppressing/extinguishing effect of these sprinklers are neglected in the study. The omitting of the sprinklers also makes the effect of smoke ventilation more distinct. This, combined with the fact that the computer software used cannot account for the effect of sprinklers by other means than lower heat release rates, motivates the exclusion of sprinkler activity in this report.

In many cases the input data used in the study are specific for the object. With this in mind, direct use of these data in risk analyses of other objects should not be made.

Performance criteria
In the results the only criterion for safety performance analysed is the smoke free height. This is the hardest criterion to be met if set at a reasonable level. This makes it possible to omit the criterions for obscuration and to analyse the effect of temperature and radiation to a lesser extent. The effect of smoke control systems on smoke temperature and radiation from the smoke to evacuating people has not been evaluated. This assumption is further discussed in chapter 5.1.

Geometry
The geometries studied are those of larger passenger ships and cannot be directly applied to smaller ships like High Speed Crafts. Simplifications of the geometry have been made in order to easier analyse the results and to meet the limitations of the computer software used.

Ventilation
In all conducted computer simulations only exhaust ventilation is taken into account. The supply air from the ventilation system is neglected. This could be done since the computer software used automatically corrects for mass flows in and out of compartments.

The spread of smoke through the ventilation system is not a subject in this report. The phenomenon is merely discussed as the risk it constitutes when running an HVAC-system to extract smoke.

2 Description of objects

2.1 General

The base for this study is the *M/S Skåne*, a Ro/Ro vessel operating in the Baltic Sea. The vessel has been used as an input source for different conditions concerning geometry, interior and configurations of the existing ventilation system.

Although *M/S Skåne* is a large ship, its accommodation areas do not fully represent the range of possible variations in geometry that are becoming more and more common in modern passenger ships. For instance, the maximum ceiling height on *M/S Skåne* is 2.2 m in all accommodation spaces. Since the mass entrainment in the fire plume, and hence the smoke produced, is dependent on the ceiling height, this parameter had to be altered. Another example is the size of the cabins. Larger, more luxurious cabins are common, and since the volume of a room affects the temperature of the smoke this also was taken into consideration. The wish to be able to use *M/S Skåne's* geometries to represent other passenger vessels, resulted in creating alternative geometries based on the *M/S Skåne*. These geometries are said to be on the fictive ship *M/S Alternative*. The studied objects are presented in a general approach below. More detailed information of input data, such as the design fire, geometry and ventilation is presented under each scenario in Chapter 5. Drawings of *M/S Skåne* are presented in Appendix J.

2.2 Description of *M/S Skåne*

2.2.1 General about M/S Skåne

M/S Skåne is a typical Baltic train ferry (Ro/Ro passenger ship) constructed in Spain in 1997. It has 11 decks and a total length of 240m. Below sea level is the tank top, deck 2-8 are cargo decks for cars, trains and trucks, deck 9-10 are accommodation decks with cabins, public areas and crew accommodations. Deck 11 consists of the bridge only, see Appendix J. The maximum number of passengers is approximately 600, and the number of crewmembers varies between 35-40.

2.2.2 Cabin area

On M/S Skåne the passenger cabins are located on deck 9 and 10. Each cabin area makes out a class A fire zone (Figure 1: Corridor in the cabin area.*)*. The cabins hold either 2 or 4 passengers and measure 3×4m^2. Deck 10 has no accommodation areas except for the cabins. They are divided into three class A fire zones, of which one is for the crew only.

Figure 1: Corridor in the cabin area.

2.2.3 Public Areas

Except for the sauna and health club located on deck 8, all public areas are located on the 9th deck. The public areas are separated into tree major, class A fire zones:

- The cafeteria with additional dining areas. (Figure 2)

Figure 2: Cafeteria on M/S Skåne

- The arcade, holding a tax-free shop, 2 lounges, a cinema, a playroom for the children and toilets. (Figure 3)

Figure 3: The arcade on M/S Skåne.

- The reception hallway. This fire zone also includes the corridor on deck 10. (Figure 4)

Figure 4: The reception hallway on M/S Skåne.

2.2.4 Ventilation system

When a fire is detected on *M/S Skåne* the HVAC-system is shut down. This action is called an "emergency shut down" and it is done in an effort to prevent the smoke from spreading through the system to unaffected zones in the ship.This report analyses three different zones of the ship. They are *a cabin area*, *a cafeteria* and *an arcade with adjoining compartments*. A separate ventilation system serves each one of these areas. The systems are all described more in detail in chapter 6.

2.3 Description of M/S Alternative

2.3.1 Cabin area

The cabin area studied on *M/S Alternative* only differs from *M/S Skåne* by the means that the cabins are somewhat larger in size. They measure 6×8 m^2 to better represent a luxurious cabin.

2.3.2 Cafeteria

On *M/S Alternative* the cafeteria incorporates two decks, making the ceiling height 4.4 m. On all other aspects it has the same geometry as the cafeteria on *M/S Skåne*.

2.3.3 Assembly hall

This is the theatre/cinema on *M/S Alternative*. The measures are about those for a normal theatre and are based on the geometries of the cafeteria on *M/S Skåne*. The altered parameter is the ceiling height, now set to 10 m.

2.3.4 Atrium

The cafeteria on *M/S Skåne* has been altered to represent an atrium of ceiling height 22 m. The atrium is based on the cafeteria on *M/S Skåne* but only makes up half the area.

3 The fundamentals of smoke control systems

3.1 Aspects of smoke movement in ships

Smoke is known as a major killer in fire situations. The usual action taken when a fire is detected on a ship is to completely shut down ventilation system, i.e. closing dampers and shutting down fans. This is done in an effort to prevent the smoke from spreading. Four driving forces mainly cause smoke movement within buildings as well as in ships; stack effect, buoyancy, wind, and the ventilation system **/19/**.

Stack effect occurs in elevator shafts, mechanical shafts and stairwells. The effect is caused by pressure difference due to two air columns at different temperatures. This pressure difference causes an upward airflow within the shaft. Largest pressure difference is caused during the winter since the temperature difference between outside and inside the ship is largest at this time of the year. In this report the stack effect will be taken into consideration since the public areas studied contains no or very low shafts.

High temperature smoke from a fire causes buoyancy. The high temperature reduces the density of the smoke, which causes it to rise. The smoke can then move through leakage areas to floors above and rooms next to the fire. As smoke travels further away from the fire the temperature drops and the buoyancy therefore decreases with the distance from the fire. The effect of buoyancy is considered both in the CFast-program and in the evaluation of the simulations.

Wind causes pressure differences on surfaces, which can cause the smoke to move within the ship. The pressure becomes positive with windward walls and negative with leeward walls. The effect of air movement within a tight construction with all doors and windows closed is slight. The window in the fire compartment often breaks due to the high temperature and pressure. If the window is on the leeward side, the negative pressure due to the wind ventilates the smoke from the fire compartment. This can reduce the amount of smoke greatly inside the ship. However, when the situation is opposite, that is that the window is on the windward side, the wind forces the smoke into the ship. This study will not consider wind-effects in any other way than to recommend that always try to manoeuvre the ship so that the wind effects the fire compartment on the leeward side.

The ventilation system can serve as a transport system for smoke through different parts of the ship in the same way as in a building if not properly designed. Pressure build-up in the fire compartment will force smoke to spread through any available openings, ventilation ducts included. This phenomenon has not been evaluated further in this report, but it was discussed in the conclusions in chapter 8 and in the proposals for different design solutions in chapter 3.2.3. Earlier studies have shown though that spread of smoke might increase as well as decrease with the normal ventilation running compared to when you completely shut down the fans **/5/**. Actions used to minimize the risk of increased smoke spread are to use dampers, especially to shut off any recirculation of air. Recirculation of air is commonly used in most ventilation systems in order to save energy.

3.2 Description of smoke control systems

3.2.1 Definitions

Smoke control or smoke management is the general name for the different methods of preventing smoke spread and can be applied on ships as well as on buildings. For ships, the two different types of smoke control are defined as **/14/**:

Active smoke control - the use of mechanically created pressure differentials and flows between smoke control zones in order to prevent smoke spreading as well as to remove smoke from the ship by extraction.

Passive smoke control - the utilization of built in barriers within the ship, such as bulkheads, fire doors, fire dampers etc. in order to enclose the fire area and stop the smoke spreading.

A smoke control system would incorporate both a passive and an active part. However, in this report "smoke control system" is used as an expression for "*active* smoke control system" since the main object of the study is the use of active smoke control systems.

3.2.2 Purpose and function

When considering the safety of people, the major hazard in a fire is the smoke being produced. A smoke control system can therefore make a significant improvement on the fire safety in any construction. By extracting the gases produced by a fire, one can reduce the negative effects such as increased temperature, lowered visibility, toxicity, explosion risk, construction damage and interior smoke contamination.

The main purposes of using smoke control systems is to /25/:

- Simplify egress by keeping escape routes, and to some extent other areas, free from hot and toxic fire gases. The goal is to meet different performance criteria set up by, for example, NFPA. The performance criterion could incorporate smoke free height, maximum temperature, radiation to evacuating people, level of obscuration etc.

- Control and stop smoke mitigation to other areas than the room containing the fire.

- Decimate the damaging impact of a fire on the constructions.

- Make it easier for the fire rescue service to perform their tasks, such as find and rescue survivors, locate and extinguish the fire etc.

- Clear affected areas from smoke after the fire has been extinguished.

These objectives are in compliance with the ones set up by NFPA (NFPA 1991b).

There are two main established methods for evacuating smoke due to a fire; natural ventilation (use of buoyancy forces) and forced or mechanical ventilation (use of fans).

Natural ventilation is the simplest way to evacuate smoke from a space. The driving forces are related to the temperature of the smoke (see buoyancy above). When placing outflow openings in the top of the compartment and additional inflow openings in the lower part, a draught that evacuates the smoke through the top openings is created. In order to work properly these openings have to lead directly outdoors and be placed so that they are not affected by wind in a negative way. Another requirement for this type of ventilation to work properly is a distinctive temperature difference between the smoke and the surrounding fresh air in order for buoyancy to occur.

A mechanical ventilation system, on the other hand, is not restricted to only handle hot smoke, and the negative effect of wind can easily be avoided by using two counter-directed outflows (see chapter 3.2.4). These advantages propose a wider use and applicability than for natural ventilation and this is most evident for the windy maritime conditions. Noticeable, though, is that a ventilation system for smoke control has to meet different requirements than a regular Heating Ventilation and Air Conditioning system (HVAC). Specific requirements for ships are yet to be determined, see chapter 4.1, but for buildings they are regulated by national laws, or by recommendations, depending on the country /25/. In Sweden the recommendations are presented by Boverket, The Swedish National Board of Housing, Building and Planning, and state the following requirements:

The fan should be able to…

- evacuate cold smoke from the initiating fire.
- evacuate smoke for a time long enough to secure egress from the premises.
- keep the premises free from smoke to such an extent that the fire brigade can locate and extinguish the fire.
- operate in a temperature of up to 300°C for the time intended, normally the time for the fire resistant construction. This could be compared to French and German regulations stating operation demands for 2 hours and 400°C or 1 ½ hour and 600°C respectively /25/.

For a typical HVAC-system in the accommodation areas of a passenger vessel all of these requirements are normally not fulfilled, probably only the first and possibly the second. Depending on the area served, for example cabins or a cafeteria, the change of fresh air differs significantly. For accommodation areas the volume of air inside the area should be changed 12 times every hour. For large volume spaces like a cafeteria or an atrium, this leads to a demand of fans with large capacities for the ventilation system serving the area. On the other hand, for a small cabin the required capacity is quite low for these comfort demands. One should bear in mind that the major part of the exhaust ventilation in a cabin area normally is placed in the corridors. These exhausts are designed to take care of the excess air from all cabins in the corridor making heavy demands on the capacity of the HVAC fans.

Beside the recommendations stated above some other aspects has to be considered. To prevent spread of smoke and fire through the system to other parts of the ship than the part on fire, the system has to be properly isolated and dampers should be used where needed. This is most important for systems that in one way or another incorporate more than one fire zone. Ducts passing through bulkheads or a system serving more than one fire zone are examples of this. The requirements for dampers and ducts are regulated in SOLAS chapter II-2. **/13/**

The fans do not only have to work in high temperatures. It is also of great importance that sparks from the fans are eliminated. These sparks could ignite uncombusted gases in the smoke with explosions as the worst consequence.

3.2.3 Technical design solutions

The technical design solutions presented here is a compilation of recommendations from experts in the field, derived from earlier research, and do not mirror the results of this report. They have been used as guidelines for the simulations carried out, presented in chapter 6, and the conclusions drawn in chapter 8.

Make-up air supply

The supply-air for the smoke control system on a passenger vessel can be taken from either separate supply fans, natural inlets through the hull, or from over pressurised adjacent compartments, like stairways. The different solutions are more or less suitable for different parts of the ship, and are treated in detail below, but the general characteristics of the make-up air supply should be **/18/**:

- The inlets should be placed as far away from the exhausts as possible, and as low as possible. As a rule the inlets should be placed below the desired level of the smoke layer, i.e. the smoke free height according to the used acceptance criterion. If air is introduced above the smoke layer interface it will simply add mass to the smoke layer. To overcome an increase in the depth of the smoke layer, this added mass must be compensated by an increase in the exhaust capacity. This is not desired.

- The air should be uncontaminated. Contamination can be prevented by making sure the supply air intakes are separated from the exhaust discharge and that recirculation of air, if the HVAC system is in use, is shut off.

- The air should be introduced at a low velocity not to adversely affect the plume, fire or smoke layer. High velocity air supply may bend the plume enhancing the entrainment rate, increase the burning rate of the fire and mix the clean air with the smoke at the smoke layer interface.

- Supply air should be provided at a rate less than the extraction rate. This precaution will prohibit a positive pressure build-up within the area, which would cause smoke to spread to adjacent communicating spaces.

Exhaust requirements

As for the supply air, some general requirements have to be fulfilled by the exhaust part of the system. These are **/18/**:

- The capacity of the smoke exhaust must account for the rate of smoke produced by the fire, but also for eventual excess airflow from the supply provided above the smoke layer interface (mentioned above). The capacity is given as the volumetric flow rate. This can be derived from the fire plume mass flow with consideration of the change in density due to temperature differences. Computer software or hand calculations can be used for this purpose.

- The exhaust intake must be located above the smoke layer interface, preferably as close to the top of the space as possible. This maximises the amount of smoke extracted and decreases the risk of extracting too much clean air. Extraction of clean air will be an unnecessary load to the system, causing the system to operate insufficiently if not considered in the design process. On the other hand, even if extraction of clean air is considered in the design process, it will lead to over dimensioned system capacities and thus unnecessary costs.

Cabin areas
For cabin areas it has been proposed by ABB Fläkt Marine AB to use a system for extraction through the corridors outside the cabins, Figure 5 /**27**/. The system is intended to be separate from the HVAC-system and intended to operate for 2 hours minimum.

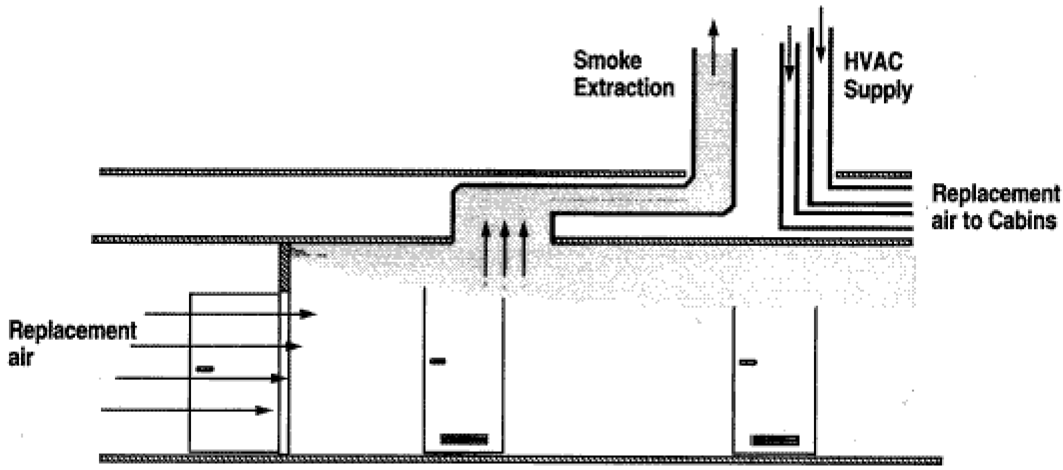


Figure 5: Smoke extraction and replacement supply air for a corridor in the cabin area. From ABB Fläkt Marine AB.

Integrating the smoke extraction with the HVAC is also possible, requiring additional upgrades to handle hot smoke. If the capacity of the HVAC system is low, additional smoke extraction fans could be used. The fans can either work together or bypassing the normal HVAC fans with the smoke extraction fans, making a separate system but with combined ducts and exhausts.

It is recommended to use the over-pressurised stairways to supply the replacement air in combination with the excess supply air from the cabins. Providing supply air from the stairways implies open doors between what normally are two different fire zones. The complete system with supplies and exhausts is illustrated in Figure 6.

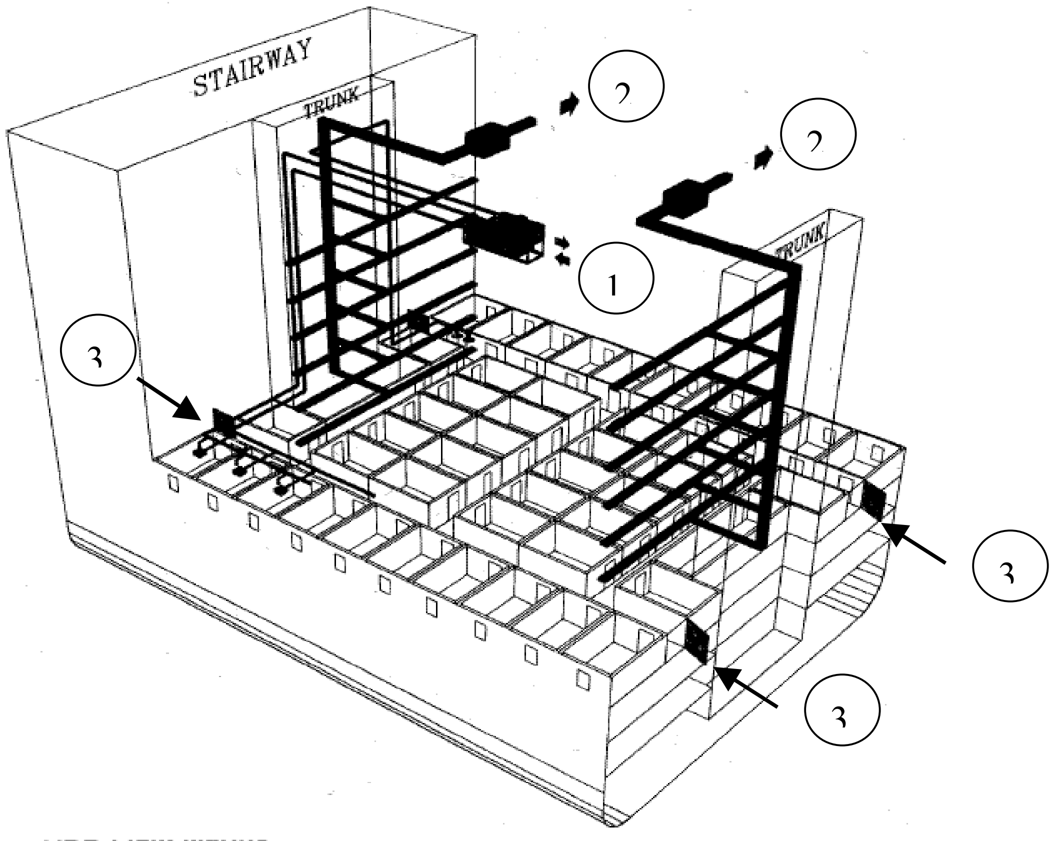


Figure 6: Complete system for smoke extraction of cabin areas. 1 – Supply and exhaust air for cabins. 2 – Smoke extraction system. 3 – Supply air from stairways through open corridor doors. As proposed by ABB Fläkt Marine AB.

Public areas and atria

As mentioned earlier, most larger public spaces like restaurants, lounges and atria are equipped with very powerful HVAC-systems in order to keep a high quality indoor climate. The use of the HVAC-system to extract smoke from these spaces would be the ultimate solution, considering saving space and unnecessary costs following the installation of a separate smoke extraction system. If not powerful enough, the HVAC could preferably be supported by supplementary smoke extraction fans, as illustrated for an atrium in Figure 7

If, for large spaces like atria and restaurants, supplementary high capacity extraction fans are needed, the supply-air will be an issue of concern. The smoke control system must be able to make up for the extracted air. The other requirements for the supply air stated above also have to be fulfilled and if this cannot be done by the HVAC itself, additional make-up air supply might be needed.

Supply air taken only from over-pressurised stairways will probably be insufficient following the high capacities required for large volume spaces. Separate air inlets, purpose designed for the smoke control system, will in that case have to be used. This air can be provided either from separate supply fans, or from natural inlets in the ships hull as proposed by ABB Fläkt Marine AB, Figure 7.

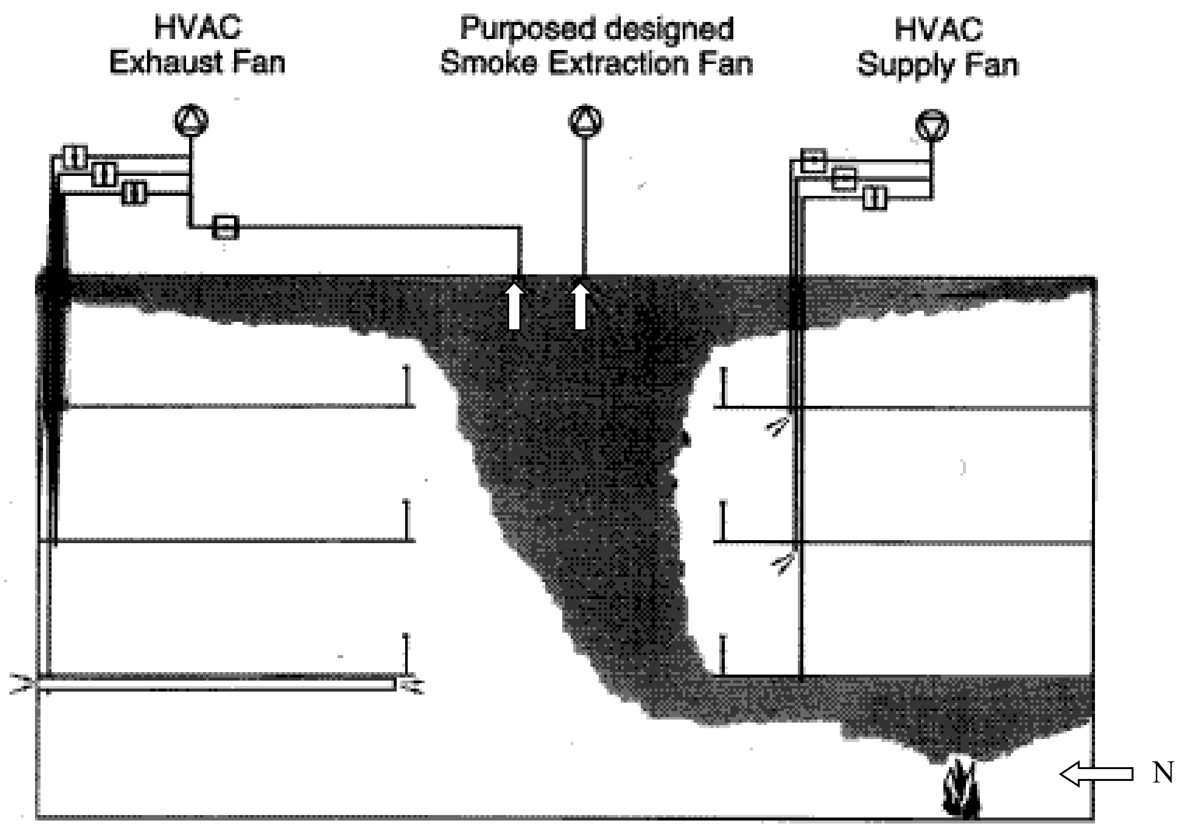


Figure 7: Smoke control system for large public spaces, atrium type. The letter N *marks the natural inlet through the ships hull. From ABB Fläkt Marine AB.*

3.3 Queen Mary 2 – an example of the use of smoke control systems

Queen Mary 2, Cunard Lines next cruise ship, is scheduled to be taken into use during the second part of 2003. Queen Mary 2 will become the most luxurious, biggest and above all the most environmentally friendly cruise ship ever built. With her total length of 345 meter she will be 45 meter longer than the Eiffel tower is high. The ship will be built on the French shipyard Alstom Chantiers de L'Atlantique in Saint-Nazaire. Queen Mary 2 will hold close to 4000 persons, 2620 passengers and 1245 crewmembers. The ship will in the beginning operate between Southampton and New York **/28/**.

Queen Mary 2 will become equipped with a smoke control system. Unfortunately, the information found about this system is very brief and seems classified. The system is designed and based on a numerous amount of scenarios; all defined by different possible fire scenarios and preventive action taken against these. All of these scenarios are defined as input to computer software and the system is also programmed to know which parts and how to activate. The system installed is called "*Smoke Control Strategy*".

4 Risk evaluation of smoke control systems

4.1 Regulations – SOLAS

Fire safety aboard ships has since 1980 been regulated by the international safety convention SOLAS 1974 (Safety Of Life At Sea) chapter II-2, a convention prepared by the International Maritime Organisation (IMO). The convention is at present in the form of a prescriptive regulation, leaving little or no room for alterative design solutions concerning the fire safety. The regulations set a minimum standard to which all Member States must conform. It is then up to every country to prepare its own individual legislation /**25**/.

Smoke control systems has been a topic of discussion during recent years, and additional regulations to SOLAS 1974 are being prepared following the comprehensive review of chapter II-2 initiated in 1991. These new requirements were decided to be issued as a circular from the Maritime Safety Committee (MSC). For this purpose, the MSC has a number of sub-committees, amongst others one on fire protection. One of the regulations under development is the draft to the Fire Safety Systems Code chapter 11 – Smoke Control Systems /**14**/.

Today, the control of smoke spread is treated in Regulation 8 of SOLAS chapter II-2. The regulation only states requirements for controlling smoke in machinery spaces, control stations, concealed spaces and atriums. The definition of atriums is according to SOLAS /**13**/: "public spaces within a single main vertical zone spanning three or more open decks". No requirements for accommodation areas in general are specified, and the smoke control in atriums is regulated as follows:

"Atriums shall be equipped with a smoke extraction system. The smoke extraction system shall be activated by the required smoke detection system and be capable of manual control. The fans shall be sized such that the entire volume within space can be exhausted in 10 min or less"

This requirement of exhausting the entire volume within the space within 10 minutes might result in a sufficient system to secure the means of egress of the passengers. But the applicability must be said to be highly limited since no consideration is taken of different fire loads (design fire size) and the stated requirement that the smoke layer should be kept at a safe level above deck in all evacuation routes, independent of their level in the atrium. These additional designfactors were the subjects for the simulations in Scenario 7, presented in chapter 6.

In addition to the low level detailed regulations on active smoke control, it should be mentioned that the passive smoke control is more extensively covered by SOLAS. Requirements are set for the structural boundaries to prevent fire and smoke spread, both through the structure and through the ventilation system.

4.2 Performance based design and the effect on smoke control systems

4.2.1 Performance based design

With the forth-going amendment of SOLAS chapter II-2, the introduction of performance based design concerning fire safety on ships is at hand. The regulation on performance based design is set out in the revised SOLAS chapter II-2 Regulation 17, which is expected to come into force on 1 July 2002.

The new regulation states two alternative ways to design fire safety aboard ships:

1. The first alternative is to use the prescriptive regulation. The regulations are the same as before but have now been given a better structure to facilitate the usage.

2. The second alternative is a performance based design. This alternative allows a maybe more cost-effective solution, which must keep the same safety level as alternative 1. To be able to use this alternative you have to prove that your solution is as safe as the prescriptive regulations.

To simplify the application of performance based design-solutions, a draft for guidelines have been brought out by the Maritime Safety Committee /**10**//**12**/. They serve to outline the procedure of the engineering analysis required by SOLAS regulation II-2/17. The Guidelines refers to fire safety engineering literature such as ISO-documents and the SFPE-handbook.

Using the methods, empirical data etc. provided by the recommended literature should be a basic demand to make the safety level of the performance based approach equivalent to the prescriptive. For smoke control systems, design methods are presented in numerous publications, for example *Klote J. H, Design of Smoke Management Systems* /**18**/.

In addition to the methods presented in literature, adequate performance criteria have to be set up to make it possible to verify the level of safety in a quantitative way. Today there are no established performance criteria specified for maritime use, but proposals have been developed by the MSC sub-committee on fire protection. These proposals are presented in the draft regulation 8 of SOLAS /**11**/ and the draft to the Fire Safety Systems Code chapter 11 – Smoke Control Systems /**14**/. The proposals incorporate performance criteria on critical conditions concerning: smoke free height, temperature, radiation levels and concentration of toxic gases. This study is limited to a discussion about the criterion on smoke free height and its effect on the design of a smoke control system.

When proper performance criteria are set, these can be used to determine the safety level of the smoke control system being designed. But when using performance based design to come up with solutions for a smoke control system the designer will also have to take the fire load of the interior in the enclosure into consideration. This is done by applying design fires based on the fire technical properties of the interior of the design object. These are specified by a heat release rate vs. time. Using different computation models, presented by, for example *Klote J. H, Design of Smoke Management Systems* and *Karlsson B, Enclosure Fire Dynamics*, the capacity of the smoke control extraction fans can be determined.

4.2.2 Smoke free height

As mentioned in chapter 4.1, the present prescriptive regulations only give functional requirements for smoke control in atriums by describing the means of activation and the extraction rate in relation to the volume of the atrium. With the utilization of performance based design, alternative solutions for smoke extraction will be possible, both for atriums and for other accommodation areas. As mentioned earlier, adequate performance criteria have to be used to verify the safety level of these alternative design solutions. But what criteria are adequate? Considering the smoke free height, the main criteria for this study, what would be the reasonable level for application on a ship? The scope of this study does not account for answering these questions, but they will be highlighted and brought to a discussion.

In this study the Swedish recommendations for the performance criteria for smoke free height was used in the risk analysis. These are presented in BBR 7 by Boverket, The National Board of Housing, Building and Planning and are in compliance with the National Fire Protection Association code. These state a smoke free height for buildings of 1.6m + 0.1×H (H = ceiling height) /6/. For a passenger ship, the normal deck height is about 2.2m and would thus make the smoke free height about 1.8m.

However, in proposals to the review of SOLAS other criteria have been presented. In the draft FSS-Code chapter 11, a smoke free height of at least half the deck height, i.e. 1.1m for most decks, is proposed for all escape routes. A counter proposal by the US suggests a smoke free height of 1.8m above the upper most deck level for atriums and public areas used as muster stations (area of refuge).

The choice of the criteria to be used will have a distinct effect on the final design considering the extraction rate of the smoke control system. The differences in the final design can be illustrated by the following example: For an escape route with the standard ceiling height of 2.2m, the NFPA method would give a smoke free height of 1.8m. If the criterion of half the deck height would be applied the smoke free height would be only 1.1m. On the other hand, for an escape route with a ceiling height of 5.0m, the NFPA method would give a smoke free height of 2.1m. With the application of the criterion of half the deck height the smoke free height would in this case be 2.5m. The distinction of the two methods are illustrated for deck heights between 2.0m and 10.0m in Figure 8.

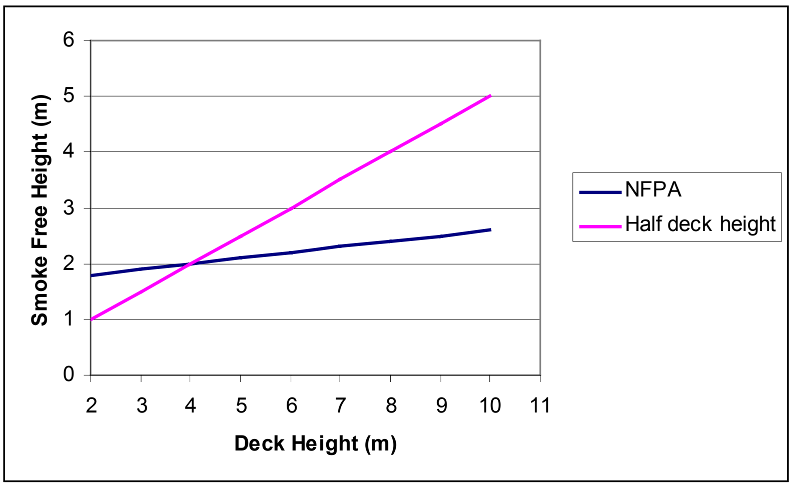


Figure 8: Smoke free heights for the NFPA and the "half deck height" criteria.

With these results in mind, one can discuss one of the main purposes of performance based design: the possibility of finding a more cost effective solution for the required safety level than the solution achievable by prescriptive regulations. To evaluate the cost of a smoke control system it can be said that the larger the smoke free height, the higher the extraction capacity needed from the system. This leading to higher costs but also to a higher level of safety. The inclination of the graphs in Figure 8 can thereby be said to illustrate the different increase rates in cost for the two criteria. Furthermore, the point of intersection at 4.0m can be said to represent the deck height where the two criteria switch places as being the most cost effective one. The NFPA criterion will give the most cost effective solution for larger deck heights, i.e. for heights over 4.0m. As an example, for the 5.0m escape route the smoke can descent an additional 0.4m compared to the “half deck height” criterion. But for lower deck heights, below 4.0m, the “half deck height” criterion will give the most cost effective solution. For the standard deck height of 2.2m the difference would be as much as 0.7m compared to the NFPA smoke free height.

The most common deck height in escape routes, i.e. corridors in general, is about 2.2m. It would therefore be of great interest, in a strict cost effectiveness point of view, to be able to implement the criterion of “half deck height” in those areas. On the other hand, does a smoke free height of 1.1m represent a tenable safety level required for an escape route on a ship? Is it rational to expect people to crouch or even crawl to avoid being affected by smoke if it can be prevented by a somewhat more powerful smoke control system?

From studying the slopes of the two graphs in Figure 8 one can see a more aggressive trend in the “half deck height” criterion. The steep incline will lead to unreasonably high extraction capacities for large deck heights, meaning higher costs, and in contrary, unreasonably low smoke levels for low deck heights, meaning lesser safety. The NFPA criterion presents a more plausible approach, and it also sets a practical minimum level of the smoke free height to 1.8m.

The paragraphs above give an idea of the difficulty of setting adequate performance criteria. To what extent should you consider the rise in costs following a more demanding criterion? How does it relate to the increased safety level? Since performance criteria on critical conditions have not yet been established for the SOLAS-regulations, a cost-benefit analysis would be a helpful tool in the decision making process.

4.2.3 Interior fire load

The results from applying a design fire to an enclosure and determining the required extraction capacity will vary with the magnitude of the design fire. Then what happens if the extraction fan capacities for a specific enclosure and fire load will take unrealistic proportions? The negative aspects of installing such a system might just be too dominating to motivate an installation, see chapter 4.3. What can be done to get around this? The solution presented, or rather discussed, in this report is to somehow limit the amount of combustible material in the interior. This will lead to the possibility of using smaller, weaker design fires, producing lesser smoke and thus requiring lower extraction capacities from the smoke control system. After all, when reducing risks it is always preferred if a risk can be avoided or prevented instead of only minimizing its consequences.

In the ongoing amendments of SOLAS, restrictions for combustible materials in accommodation areas on passenger ships have been presented. These require a replacement of combustible interior, i.e. surface and lining materials, by incombustible on all existing passenger ships by the year of 2005 **/9/**. Furniture as part of the interior is scarcely covered by Regulation 5 in SOLAS chapter II-2, stating requirements for stairway enclosures and escape routes.

By following the prescriptive regulations, the fire load from the interior will automatically be decreased. But by the implementation of alternative solutions based on performance based design there also is an opportunity not to follow the prescriptive regulations. The designer of a smoke control system would then be able to decide how much combustible interior that will correspond to the required safety level. If the wish is to minimize the size of the smoke control system, restrictions on the interior could be made in a way that decreases smoke production and heat. This will of course incorporate furniture as well as surface and lining materials.

For this to be possible one condition has too bee fulfilled though; information on the fire specific properties of materials used in ships interior has to be accessible. Using data for the design fire based on a material not representative for the real interior of the enclosure may generate over as well as under dimensioned requirements for the smoke control system. This will constitute a great risk for the designer to consider, both in the way that the required safety level may not be achieved by an under dimensioned system and in the way that costs will rise for an over dimensioned system. A study carried out in Sweden 1992 highlights the importance of this information being accessible as well as the shortage of information at the time of the study **/1/**.

4.3 Negative aspects on smoke control systems

One seldom finds a solution to a problem that does not generate new predicaments when you try to put it into practice. So is the case with an active system for smoke control. The positive aspects listed in the previous chapter strongly motivate the use of such a system but the negative aspects and complications have to be considered. In this study the purpose is not to present solutions for how to handle these predicaments. They are merely discussed as a part of the risk assessment made on smoke control systems in ships as a whole. However, solutions are presented to some extent in chapter 3.2.3 as well as in the final conclusions in chapter 8.

4.3.1 Occupied space

The major problem in a passenger vessel is to minimize occupied space and installation costs for air handling units and ducts so that as much space as possible can be used for other, more cost-effective purposes, like accommodation areas. This interferes with the idea to install separate systems for smoke extraction since these cause high demands on duct and fan capacities. The possibility of integrating the smoke control system with the HVAC-system, discussed in chapter 3.2.3, is thus an interesting alternative.

4.3.2 Pressure loss

When reducing the total number of air handling units, longer ducts are required to cover all areas of the ship. Long ducts causes the pressure to fall due to friction and resistance in bends, branches etc. For a smoke control system you wish to minimize the pressure loss to get as much capacity as possible out of the system.

4.3.3 Dampers

Long ducts, passing through bulkheads and main fire zones, also require fire dampers to prevent smoke spread between the fire zones. Dampers, as most mechanical devices, are in need of maintenance on a regular basis and should therefore try to be kept as few as possible. It is not unusual with as many as more than 500 dampers on a large cruise liner /**21**/, not only making the maintenance demanding but also making the operation and monitoring of the dampers complex and time-consuming.

4.3.4 Make-up air supply

A factor that is significant when dealing with smoke control systems aboard ships is the integrity of the ships hull. The indoor climate in a modern passenger vessel is controlled by an air-conditioning unit in order to keep the climate at passengers delight. As a cause of this the natural ventilation through leakages in the hull or open doors to sun decks can be considered as non-existing why this type of air supply basically can be disregarded. The windy conditions at sea can be said to make the integrity of the hull a general problem considering natural ventilation, no matter what the outside temperature might be. The problem can be solved by additional openings or a supply air ventilation system, as mentioned in chapter 3.2.3.

As also mentioned earlier, supply air can, if not properly provided, cause turbulence in the plume and smoke layer as well as unwanted over-pressurisation of the smoke filled space.

4.3.5 Noise

When running any ventilation system, fans, motors and airflow will create unwanted noise that propagates through the ducts /**20**/. The higher the capacity of the system, the more noise it produces, and since a smoke control system demand high capacities one could expect interference with the fire alarm system during operation. The use of Public Address systems, PA-systems, during evacuation may be negatively affected by too loud noise from the smoke control system.

4.3.6 Supply of additional oxygen

Since the presence of oxygen is a necessity for a fire to develop, the aspect of providing the fire with additional air via the smoke control system must be considered. This problem is most evident for a fire that has become ventilation-limited, i.e. there is a sufficient amount of fuel but a lack of oxygen. Under these circumstances uncombusted gases are produced, and if oxygen is presented at this stage the risk for an explosion is at hand. For a space equipped with a smoke control system the fire normally would not become ventilation-limited if the system starts to operate immediately, both exhausting smoke and providing supply air. But if the activation of the system somehow would be delayed, letting the fire become ventilation-limited, the problem with an explosion may be impending as the system starts feeding the fire with oxygen. This is especially an issue when the system is activated manually. In a situation like that one must be certain of the conditions of the fire to make the decision whether or not to activate the system /**3**/.

4.4 Reliability of smoke control systems

When assessing the reliability of a multi component system, like an active smoke control system, one would normally use the fault tree analysis method to obtain a quantitative result. Today, however, very few systems for maritime use can be accounted for and it is difficult to obtain data about the reliability of components. Not even one of Sweden's largest manufacturers of ventilation systems could assist with data on the matter. Making a fault tree analysis with insufficient data of a "representative" system just in order to obtain a quantitative result is therefore not of interest. A more practical approach would, in the authors' opinion, be to discuss the different factors affecting the reliability in a more qualitative manner. The discussion is based on similar discussions carried out in other literature but this time with a maritime twist /**18**/.

Any mechanical and technical system is in need of continuous testing and maintenance in order to work properly. A system for smoke control is not an exception from this but can rather serve as a typical example for the importance of acceptance and routine testing as well as keeping the systems complexity at a manageable level.

4.4.1 Testing and maintenance

Once a year, the smoke control system shall be inspected by the Administration, in Sweden the National Maritime Administration, to secure that the system is intact. If the system fails this inspection, the ship will be taken out of use until measures have been taken. When, or if, the system works faultlessly the liability of the systems testing and maintenance then lies on the shipping company.

The IMO´s ISM-code, International Safety Management Code, reviews the quality assurance system. This is a document corresponding to the ISO 9000. This quality system means that routines and instructions are well surveyed, systematized and documented. This management system also regulates the action towards more safe routines, partly to avoid accidents and partly to act correctly of an incident appear. The quality assurance system is collected in manuals, located aboard the ship and at the shipping companies head office. The manuals in the head office describe the organisation and activity of the company. The ones aboard describe the operational safety organisation and the routines that shall be fulfilled aboard to secure a safe operation of the ship.

In the draft regulation for the Fire Safety Systems Code chapter 11 - Smoke Control Systems, test procedures for acceptance testing and periodic testing are treated /**9**/. This preparatory acceptance testing (commissioning) followed by continuous routine tests constitutes the foundation of any systems level of reliability. Correcting defects detected in the acceptance test before the system is being put into use and then continuously making new corrections during the lifetime of the system will eliminate, or at least reduce, unexpected malfunctions.

If the acceptance test for some reason should be left out, a multitude of errors concerning the reliability of the system might be overlooked. Errors originating from manufacture, transport, storage and installation will not be detected and problems such as motors not being properly connected to power or wired for the wrong voltage, dampers failing to close, fans running backward etc. might occur. Practical problems, like insufficiency in the air supply, doors that are supposed to be open are closed and vice versa, will also pass unnoticed.

When regarding the risk of not carrying out the vital tests on a smoke control system one could bear in mind the advantage of having the system partly or completely integrated with the HVAC-system. It is a fact that the wish to meet passengers demands for a comfortable indoor climate will result in carefully carried out testing and maintenance of the HVAC-system components. Integrating the two systems will result in a high maintenance rate, and thus a high reliability of the smoke control system **/18/**.

4.4.2 The complexity of systems

The more features you want out of a smoke control system the more technology you have to put in. A system only designed to extract a certain amount of smoke from a limited confined space might just comprise a power system, a smoke detector, a fan for extraction, a fan for supply-air and some ducts. But a smoke control system could just as well, beyond this, incorporate a multi detection system, a sprinkler or a fire alarm system, fire doors and other barriers like draft curtains and, of course, a large number of dampers **/4/**. All components mentioned above are normally controlled and supervised from a main control unit.

As a simple, but vivid, example of how rapidly the reliability of a system decreases as the system grow, one can use the expression for reliability of a series system, i.e. a system that operate only if all its components operate. The reliability, R, of a series system is the product of the reliability, R_i, of its components:

$$R = \prod_{i=1}^{n} R_i = R_1 \times R_2 \times .... \times R_n$$

The specific component reliabilities can be arbitrary chosen since this is only a demonstration of the effect of system complexity. The following reliabilities were chosen for a new smoke control system that has not been tested for acceptance **/18/**:

Fans of a forced-air HVAC-system	0.99
Other components	0.94

Table 1 lists the reliabilities for three different systems of the sort mentioned above. The trend is distinct. The more complex the system, the less likely it is to operate.

Table 1: Estimated system reliability

System #	Number of HVAC fans	Number of other components	Reliability of system
1	1	2	0.87
2	3	10	0.52
3	3	30	0.15

With all these different systems and components interacting you do not only face the problem with their internal reliability. A complex system is difficult to manoeuvre and the possibility of human mistakes happening increases with the complexity. This highlights the issue of human reliability, a topic not further treated in this report.

4.4.3 Weaknesses of the system

Without accurate data for reliability of the components in a modern smoke control system the weakest parts of the system are hard to target. However, according to experts in the field typical weak spots of air-handling units are the motors, the bearings and the belts /**27**/. Since the smoke control system should be supervised by a main control unit, another weak spot would reasonably be the interdependence with the electricity supply. A fire could interfere with the electrical installations or they could be sabotaged by other means. A back-up power supply is however a requirement for all types of active fire protection systems on ships, see FSS Code chapter 8 /**14**/. The purpose is to secure the power supply in case of a break down of the main generator.

4.5 Evaluation of economical risks

The introduction of performance based design will lead to a number of different design solutions for the fire safety. Each one of these solutions has to be evaluated with respect to the consequences they might bring. When the public hears the word "consequence" connected to a catastrophe or an accident most people think of losses of human lives and, of course, personal losses and injuries are the most important things to prevent. But the economical risks caused by an installation of a smoke control system also have to be evaluated. They will appear not only when the catastrophe occurs but also through the whole construction process i.e. at the decision making stage, the design stage etc. Economical risks and consequences incorporate not only the actual installation costs for the smoke control system, but also the costs of personal injuries, property damage and secondary consequences.

4.5.1 Personal injuries

As shown in this report a correct designed smoke control system improves the conditions during an evacuation. As smoke is being extracted the amount of toxic substances decreases in the affected enclosures and therefore also, among others, the risk for carbon monoxide poisoning. In correspondence with this, the smoke control system reduces the risk for personal injuries. Still, everyone knows that "the unpredictable" do happen and when it does it often involves injured people. Personal injuries due to a fire will imply an economical risk for the shipping company as well as for the society.

A big tragedy, with many wounded or dead often brings fear for this activity to the public. This fear may result in lesser passengers over a period, which results in an economical loss for the shipping company.

Society has tried to define the value of a human life. Research on traffic safety has been carried out, showing how much the Swedish people are willing to pay for a risk reduction for a fatal injury due to a traffic accident /**24**/. The data was collected from individuals between the age of 18 to 74, all with different incomes, lifestyles, cars, driving routine etc. The value stated in the report, SEK 22.33 million, cannot be said to be all together valid for fires aboard ships since it is based on research in traffic accidents. It might not be the correct value for what people would be willing to pay for a risk reduction for a fatal injury due to a fire aboard a passenger ship. However, it gives a good guideline for the value of a human life. This figure can be said to correspond to the national economic risk that the society accepts.

4.5.2 Property damage

Many decisions are based on the economic costs that they generate. The actual cost to install a smoke control system will not become the determining factor for the decision of whether to go through with the investment or not. Compared to the total costs for a new built ship, the cost for an installation or upgrading of a smoke control system can be neglected. An HVAC-system constitutes about 10% and a separate smoke control system about 0.3% of the total project costs for a typical large passenger ship **/27/**.

If some part of a ship catches fire, big parts of the ship will be contaminated by smoke and damaged by heat. After a fire the ship will be in need of decontamination and repair. To what extent depends on which parts of the ship the fire and the smoke incorporates. Property damage is a big risk to consider for the management of the company. They have to decide how much reparation and decontamination costs they can accept and afford. Depending on the size and location of the fire, these costs will vary. A smoke control system affects this relation since an effective smoke extraction will bring less smoke and heat damage within the fire zone. On the other hand, a separate smoke control system or one integrated with the HVAC-system, which is used in the purpose to evacuate smoke, will have to be decontaminated and/or repaired after an incident. So, the management has to decide whether they are:

1. willing to pay for a smoke control system, which will be in need of decontamination after a fire, or

2. if they are able to risk that the interior most probably will have to be replaced after a fire.

Above this decision the management of the company has to evaluate whether the chosen solution/system achieves the safety level they desire concerning personal injuries and secondary consequences.

4.5.3 Secondary consequences

A catastrophe, which includes important, vulnerable or bigger parts of the activity of a company, might cause secondary consequences. Secondary consequences caused by a fire aboard a ship are for example a longer interruption of the ships traffic. For a small shipping company, with no replacement ships, this will strike hard on the economy of the company. Secondary consequences, caused by a fire, which affect a ventilation system is for example:

- a breakdown of the HVAC-system. This may happen if the system is used during an evacuation but has not been designed for this.

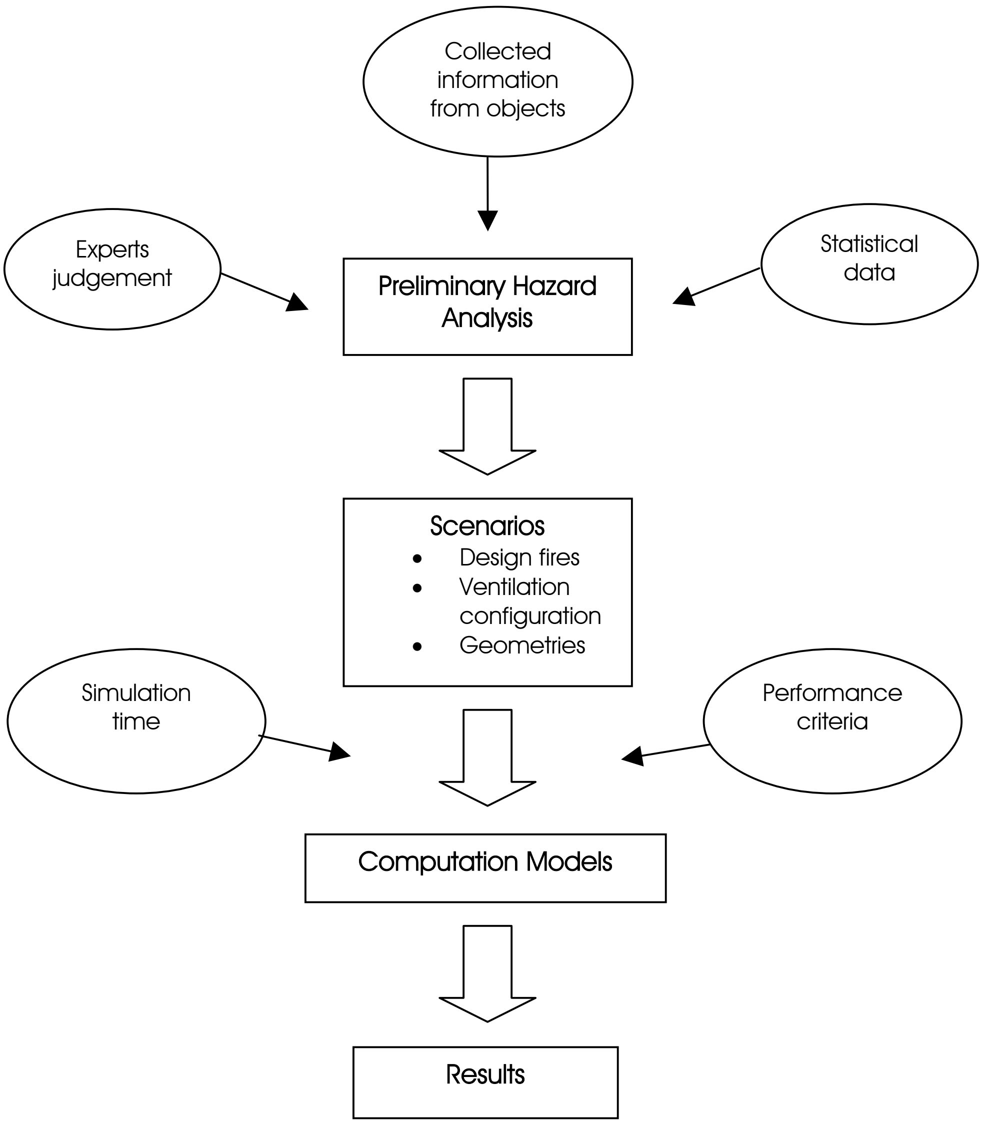
- a breakdown of the smoke control system. If a system is operating longer than the design time, the system will have to be replaced by a new one. In any way, a system that is active during a fire will need more or less decontamination.

Any of the consequences mentioned above are not caused by the smoke control system; the fire causes them. As written before, the ship will be in need of decontamination after a fire, independent of if the ship has a smoke control system installed or not. What the smoke control system will do is to lessen the damage on the interior. One cannot generally state which of a smoke control system and the affected part of the ship will take the longest time to decontaminate. This is very much depending on in which part of the ship the fire is located.

Therefore, an installation of a smoke control system should not raise the economical risks concerning secondary consequences for a shipping company.

5 General assumptions for the quantitative risk analysis

In making the quantitative risk analysis, a number of assumptions and limitations had to be made in order to obtain results that are feasible. The process of the analysis involved several steps, illustrated in the chart below. This chapter provides a description of the general assumptions and limitations made for the analysis concerning the performance criteria to be used, scenario identification and computation models. The assumptions made for each specific scenario is presented in chapter 6.



5.1 Performance criteria

The evacuation time always has to be shorter than the time it takes for critical conditions to occur inside a building, or a ship. Parameters used to evaluate the level of critical conditions are for example visibility, radiation from the smoke layer, temperature, toxic gases and a combination of these. The performance criteria used in this report follow the Swedish recommendations stated by Boverket, The National Board of Housing, Building and Planning, BBR 1998:38 /5/:

Visibility: The smoke free height, i.e. the height from the floor to the smoke layer, always has to be higher than $1.6 + (0.1 \times H)$ meters, where H is the ceiling height.

Temperature: A maximum temperature of 80 °C in the air below the smoke layer.

Radiation to a target (person): A short radiation intensity of maximum 10 kW/m^2 or a short heat release rate of maximum 60 kJ/m^2 added to the energy from a radiation of 1 kW/m^2.

The main criterion in this report is visibility. It should be observed that it is only the height of the smoke layer, and not the level of obscuration in the smoke that is used as a criterion. The criterion is set for escape routes and communicating spaces leading to escape routes. The other criteria have been taken into consideration during every simulation, and they have not been exceeded.

Using the smoke free height as the main criterion will produce conservative results, as this is the hardest criterion to meet if set at a reasonable level. This may lead to somewhat over estimated extraction capacities since tenable conditions can be achieved even with a smoke layer lower than the level that is said to be critical. To analyse this, however, one has to study the obscuration of the smoke as well as the amount of toxic gases produced by the fire. In this study the purpose is to find the maximum required capacity and to compare this with the normal HVAC. The maximum capacity is best estimated with the hardest criterion, that is the smoke free height.

The United States has, during the work with new SOLAS chapter II-2, presented a proposal concerning, among others, a performance criterion for the smoke control system. In this proposal they suggest that /12/:

"Smoke from atriums… shall be extracted in a quantity that keeps the spaces sufficiently free from smoke so as to limit the depth of the overheated smoke layer so that the bottom of it is kept to a minimum of 1.8 m above the deck. For atriums, the deck level used for this criterion shall be considered to be the uppermost deck level to which passenger or crew have access."

This criteria has been taken under consideration in the simulations, chapter 6.7 and 7.7, as well as in the evaluations, chapter 8.5, of the atrium scenario.

5.2 Hazard identification

5.2.1 Statistics

To identify possible (or more and less likely) hazardous incidents, a qualitative method for risk assessment has been used. Based on the study of possible hazardous locations in the object, interior materials, statistical data on fire incidents, expert judgement and a little common sense, a list of these possible scenarios can be set up. To be able to decimate the number of scenarios, that is to eliminate the less likely incidents, a good statistical base is of greatest importance as a support to expert judgement.

Fortunately, fires aboard ships have been documented since 1800, though more in detail during the 20th century. This documentation presents statistical data from close to 2500 incidents over a time period of 200 years. The origin and cause of fires may not have been documented in all cases, and the data may not be accepted as statistically significant, but it still makes out a good base when identifying possible hazards. The statistics have been recorded first by the Liverpool Underwriters Association and later by the Institute of London Underwriters. Information on most 2000th century incidents can be found in Rushbrook´s Fire Aboard /25/. As a supplement to this, national statistics from the Swedish Maritime Administration can be used to determine fire frequency, probable locations of outbreak as well as the cause of fire.

5.2.2 Location of fire

Statistics on the location of fire outbreak on ships is presented by the Institute of London Underwriters in Figure 9. The statistic is based on data collected from year 1977 to 1986./25/

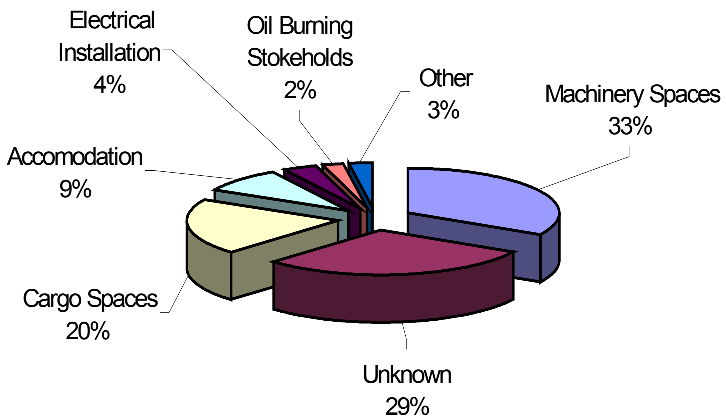


Figure 9: Location of fires 1977 to 1986 on ships in general.

Of all fires on ships, 9 % originates in the accomodation area. In the statistics found one does not define where the 4 % refered to electrical installations originates. For these 4 %, as well as for the 29 % unknown, one can assume that they partially could be included as accomodation fires. In this report, fires in engine rooms and on car decks will be disregarded.

Statistics concerning the cause and size of the fire has not been found. In literature arson is often mentioned as the cause of a fire but one can never predict where the arsonist locates it. The deed of an arsonist will not be considered in the preliminary hazard analysis, chapter 5.2.3, in any other way then to state that for all of the scenarios an arsonist is a possible cause.

5.2.3 Identifying scenarios

The semi-quantitative risk analysis method used to determine the worst probable scenarios is a method called PHA, or Preliminary Hazard Analysis /15/. This type of analysis is mainly used as a first step to identify and estimate the possible hazards on a low-detailed level in existing structures. The purpose is to decide which hazards are in need of a more extensive analysis. This decision is based partly on the evaluated level of risk, i.e. probability and consequence. But it is also based on the location of the hazard since it is of interest to study how the location of a fire affects the final conditions like temperature, smoke spread etc. In the latter the purpose is to give preference to scenarios that affect different parts of the ships accommodation areas.

Table 2: PHA of hazardous fire incidents on M/S Skåne.

Fire Scenario	Possible origin and cause	Possible consequence	Evaluated risk		Further analysis
			Prob.	Cons.	
Cabin	Smoking in bed	Smoke spreading to cabins, corridors, hallways and stairs. Spread of fire to adjacent cabins is possible.	3	H: 4 P: 2	Yes
Children’s playroom	Playing with fire	Smoke spreading to arcade, lounges, tax-free and cinema.	3	H: 4 P: 3	Yes
Kitchen	Deep fryer	Local fire, early suppressed by crew or CO_2-system.	3	H: 1 P: 1	No
Tax-free shop	Alcohol pool	Pool-fire, fast development of fire but initially modest smoke production.	2	H: 3 P: 3	No
Cafeteria	TV-set Smoking	Smoke spreading through cafeteria, driver’s room and stairs to deck 10.	3	H: 4 P: 3	Yes
Air-seat lounge	TV-set Smoking	Smoke spreading to arcade, lounges, tax-free and cinema.	2	H: 2 P: 2	No
Sauna	Over-heated	Probably small, separate fire-zone	2	H: 1 P: 2	No
Cinema	Electrical equipment Smoking	Smoke spreading to arcade, lounges, tax-free and reception hallway.	3	H: 4 P: 2	No

Table 2 lists eight possible fire scenarios and their consequences for the accommodation areas of *M/S Skåne*. The risk levels, probability/frequency and consequence, are rated on a scale from 1-5 where 5 is the most probable/worst. The consequence is divided into effect on humans (H) and property damage (P). These risk levels are presented in the risk-matrix below, Table 3, illustrating the meaning of the assumed frequencies and consequences by the means of damage costs and effect on health. Using the statistical data and experts judgement mentioned above, the risk levels were estimated. In the PHA, fires in electrical installations possible of causing a breakdown of the smoke control system were omitted. This problem is however indirectly treated in the "no ventilation" simulations described in chapter 5.3.1.

Table 3: Risk-matrix illustrating the risk-levels of 1-5 and their meaning by the means of frequency and consequence, i.e. damage costs and effect on health.

	1	**2**	**3**	**4**	**5**
> Once per year					
Once per every 1- 10 years				High	risk
Once per every 10-100 years		Medium		risk	
Once per every 100-1000 years					
< Once per every 1000 years	Low	risk			
Property	*<0.1 million SEK*	*0.1- 1 million SEK*	*1- 5 million SEK*	*5- 20 million SEK*	*>20 million SEK*
Health	*Temporary mild discomfort*	*Single cases of wounded, lasting discomfort*	*Single cases of seriously wounded, lasting discomfort*	*Single cases dead or seriously wounded*	*A few dead or serious wounded*

5.3 The contents of the analysis

5.3.1 Ventilation set-up in general

With consideration of location, three of the scenarios from Table 2 were chosen to be objects for further analysis. The chosen fire scenarios are the ones originating in the cabin, the cafeteria and the children's playroom. These design fires have also been applied to *M/S Alternative's* geometries, with some changes made. This resulted in a total of seven scenarios, shown in Figure 10. All scenarios have been further analysed in computer simulations. The design fires are presented in detail for each scenario in chapter 6.

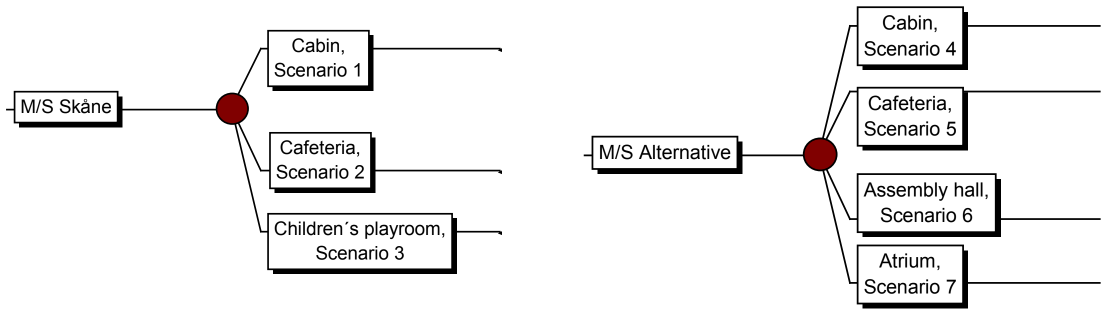


Figure 10: Event tree of fire scenarios on M/S Skåne and M/S Alternative.

Three different ventilation configurations were added to scenarios 1, 2 and 3 in Figure 10. That is the ventilation system was:

- **not** activated, corresponding to an "emergency shut down" situation or a total breakdown following for example an electrical malfunction,
- activated with the capacity of the **existing** HVAC-system installed,
- activated with the capacity **required** to keep escape ways and communicating spaces free from smoke to such an extent that the performance criteria of BBR are fulfilled.

The capacities of the existing HVAC-system on *M/S Skåne* have been measured when the system was installed. Test sheets report both the designed capacity and a measured capacity of the system. The capacity used when evaluating and comparing the HVAC-system to regulations is the designed capacity in this report. For most of the served compartments the measured airflows are higher than the compartments designed capacity. This shows that the HVAC-system is designed with a safety margin. This will be important to keep in mind in chapter 6.2.3.

Since *M/S Alternative* is a fictive object without a specified existing ventilation system only the "no ventilation" and the "required ventilation" capacity configurations were added to scenarios 4, 5, 6 and 7 and used in the computer simulations. To be consistent in the analysis, fictive capacities for existing HVAC-systems on *M/S Alternative* were calculated. These were not used in the simulations but only used for comparison with the required capacity for the public spaces on *M/S Alternative*. These capacities are based on a requirement for the air conditioning system to achieve comfortable conditions in accommodation areas on ships. It implies that the air in the entire space should be changed 12 times per hour.

To find the required smoke extraction capacities, each scenario was simulated with various capacities on the extraction fans. Using a trial and error process, starting with low capacities and increasing until the performance criterion for each scenario was fulfilled, the required capacities could be determined.

For each scenario the required capacities were compared to either the existing HVAC-system (Scenario 1-4) or to the fictive HVAC-system with a capacity of 12 changes/hour (Scenario 5-7) as well as to the “no ventilation” setup.

The purpose of studying these three different configurations is to get a clearer view of the differences between not using extraction at all, using the normal HVAC-system for extraction and using a smoke control system designed on basis of a design fire.

When simulating the different configurations with the existing and required ventilation capacities, only the exhaust air was taken into consideration. This meaning that supply air from additional ventilation systems was not used in the computer modelling. The only source of supply air used was openings in the fire compartment directly to the “outside”. This could be done since the computer software automatically corrects for mass flows in and out of compartments.

The specific ventilation configuration for each of the scenarios is described under the individual scenario. For all scenarios the assumption was made that the fans are linked directly to “outside”, that is the effect of ducts have not been considered. The consequence this brings is that pressure losses are neglected, resulting in somewhat under dimensioned extraction capacities. Information on ducts was available for the *M/S Skåne* scenarios only, and to maintain a consistency in the analysis it was decided not to include ducts at all.

5.3.2 Computation models

The quantitative risk analysis was based on computer simulations carried out on the computer software CFast, a two-zone model for prediction of smoke spread. The pros and cons of this software are well documented and its function and limitations are discussed in Appendix H. To limit the extent of this study, however, the uncertainties using this software have not been further analysed. It has simply been used as a tool to estimate smoke spread, but with uncertainties well in mind during the analysis of the results. Applying two-zone models to large volumes, like high atrium structures, is often considered uncertain since the smoke temperature often is too low for a clear stratification to occur. Therefore the stratification of the smoke layer has to be assured by studying the temperature of the smoke.

The design fires have been based on full-scale experimental data compiled by *Särdqvist* /26/ and hand calculations of the heat release rate. The heat release rate for hand calculated design fires was assumed to follow the development of $Q = \alpha \times t^2$, where α is the growth factor according to NFPA and t is the time. Hand calculations have been used only to obtain and verify the heat release rates for some of the scenarios. The calculations and methods used are further presented in Appendix I.

The effect of sprinkler systems on smoke spread and on the operability of the smoke control system was omitted in the study. This was mostly for the purpose of analysing the worst probable case but also due to the difficulty of calculating and simulating smoke spread in more complex geometries with sprinklers regarded. For more complex geometries computer programs present the most accurate results, but today there are no computer programs that in a satisfactory way consider the interaction of a sprinkler system and a smoke control system. However, for a single enclosure scenario hand calculations and a computer model are presented by *Cooper* to be used for enclosures with natural smoke ventilation, i.e. ceiling vents and not fans /7/. The same author has developed a model for simulation of the interaction of sprinkler in a two-layer (two-zone) fire environment /8/. Neither of these models was considered to be applicable to the geometries in this study.

5.3.3 Design evacuation time

The design evacuation time was set to 15 minutes. A "real" evacuation will be completed, that is the passengers will be in the lifeboats, within 30 minutes on *M/S Skåne /29/*. Based on this information the simulation time should have been chosen closer to 30 minutes, but due to the limitations in CFast a shorter simulation time had to be used. The computer program had a tendency to crash when simulating more than 15 minutes, with complex geometries and ventilation configurations. It is not unreasonable though to assume that evacuation to muster stations, area of refuge, will have been completed within 15 minutes for the studied scenarios.

6 Scenarios for the quantitative risk analysis

This chapter presents the essential assumptions made in each analysed scenario, concerning design fire, geometry and the configuration of the HVAC-system and the smoke control system. The data input files for the computer simulations were planned to be presented in the Appendix, but were finally omitted from the report due to their size.

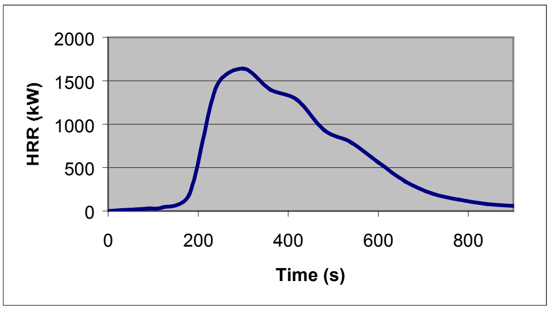
6.1 Scenario 1 – Cabin on M/S Skåne

6.1.1 Design fire

The analysed fire is one starting in one of the cabin beds, reasonably as a consequence of smoking or arson. The fire then spreads to adjacent beds reaching a total heat release rate (HRR) of approximately 1700 kW after 5 minutes. The development of the fire after 5 minutes is taken into account in the sensitivity analysis. The sensitivity analysis includes one fire with a decay phase, equivalent to full-scale experimental data /25/ as well as one more conservative fire (longer lasting in this case) with the same growth phase but with a continuing constant heat release rate of 1700 kW, Figure 11 and 12.

To verify the maximum possible HRR hand calculations were carried out. Based on simulation results there will be a flash over in the cabin (> 600 °C). An equation based on the opening factor, /15/, can therefore be used resulting in a maximum HRR of 2.1 MW for the cabin geometry, see Appendix I.

The presence of natural leakage areas in cabins and the presumption that the cabin door will be blocked open, excludes a ventilation-limited fire. Rather the fire will be fuel-limited and most probably have a decay phase according to the full-scale experimental data. Therefore detailed simulations were only carried out on the decay phase fire, Figure 11.



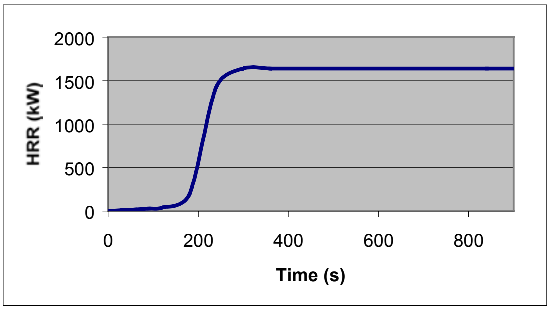
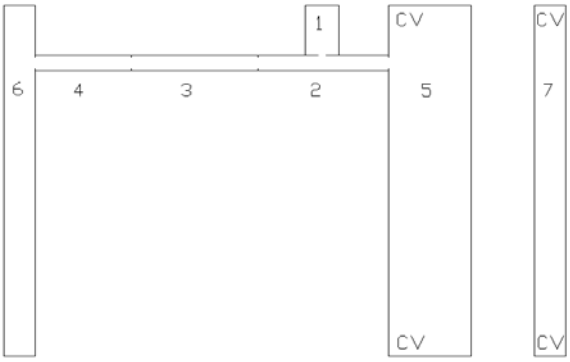


Figure 11: Heat release with a decay phase. *Figure 12: Heat release with a constant HRR.*

6.1.2 Geometry

The simplified geometry for the computer simulations of the cabin fire on M/S Skåne, Scenario 1, is presented in Figure 13. The ceiling height is 2.2 m for all compartments.



The compartments are numbered from 1 to 7 representing:

1. Cabin – fire comp. (3.0m×4.0 m)
2. Corridor, part I (10m×1.2m)
3. Corridor, part II (10m×1.2m)
4. Corridor, part III (7.5m×1.2m)
5. Reception – Hallway (28.0m×6.5m)
6. Hallway (28.0m×2.5m)
7. Hallway on deck above. Connected to compartment 5. (28.0m×2.5m)

Figure 13: Geometry for simulations in CFast.

The studied corridor has a total length of 27.5 m, and is divided into three parts by fire resistant doors. To increase the accuracy of the simulation results, the corridor outside the cabin was divided into three compartments (comp. 2, 3 and 4) in accordance with the placement of the doors. This separation was done mainly because of the limitations in CFast and since there is a natural compartmentation of the corridor due to Swedish regulations /9/. The smoke will spread in a more realistic way with this separation. (Figure 14)

Figure 14: Doors dividing the corridor into three compartments.

6.1.3 Ventilation configuration

The different configurations for the simulation of the smoke control system are presented in Figure 15.

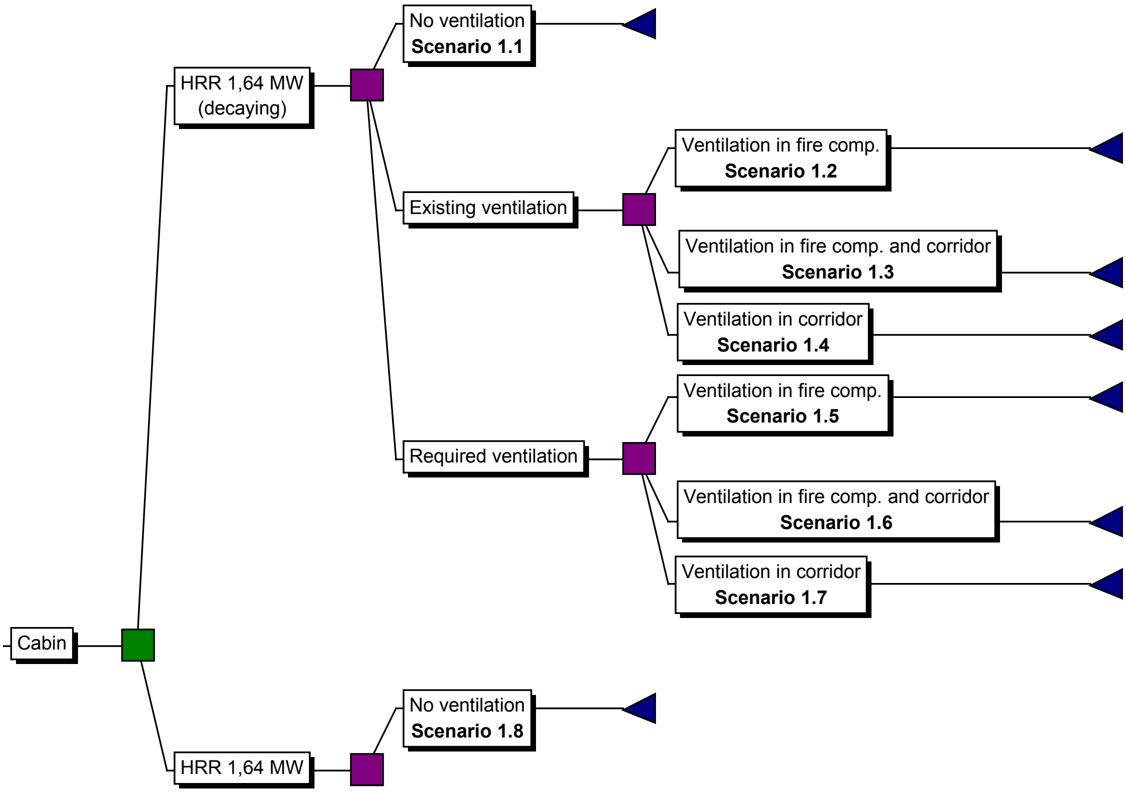


Figure 15: Event-tree for the simulated scenarios (cabin).

The existing HVAC-system for the studied cabin area is made up of one supply and one exhaust system. The air is supplied to each cabin and partly exhausted via the toilet at a rate of 63 m^3/h (0,0175 m^3/s). The excess air is transferred from the cabins to the corridor and the magnitude of this can be calculated as the difference between supply air to each cabin and the exhaust from the cabin toilet. The supply air differs between 2- and 4-bed cabins (135 m^3/h and 240 m^3/h respectively) and for the studied corridor the total excess air is approximately 2340 m^3/h (0,65 m^3/s). In other words this is the capacity for the exhausts in the corridor. In the simulations these exhausts are placed one in each of the three parts of the corridor, each with a capacity of 0,22 m^3/s.

For the simulated scenarios one can easily make the conclusion that the exhaust from the fire room of 0,0175 m^3/s is negligible in comparison to the exhaust of the corridor of 0,65 m^3/s. This conclusion leads to the assumption that Scenario 1.2 will have an equal outcome as Scenario 1.1 and in the same way Scenario 1.3 will have an equal outcome as Scenario 1.4. Hence, simulations of Scenarios 1.2 and 1.3 are considered as unnecessary.

For the case of finding the required ventilation capacity to meet the performance criteria of BBR, three options were considered: Extracting smoke through the toilet exhaust (Scenario 1.5), through the corridor and the toilet exhaust (Scenario 1.6) and finally through the corridor exhausts alone (Scenario 1.7). The same set up for the exhausts as for the existing ventilation was used; the only change made was of the capacities. For Scenario 1.5 the minimum capacity was set to 4,0 m^3/s. For Scenario 1.6, when using existing HVAC in the corridor of 3×0.22 m^3/s, the minimum capacity for the toilet exhaust was set to 3,0 m^3/s. Finally, for Scenario 1.7, the capacities of the corridor exhausts was set to 0,70 m^3/s each.

The configuration and capacities of the smoke control system for existing and required ventilation is presented in Table 4.

Table 4: Distribution and capacities of exhaust ventilation for smoke control used in computer simulations.

Compartment #	**Existing ventilation capacity (m^3/s)**	**Required ventilation capacity (m^3/s)**		
	Scenario 1.4	Scen. 1.5	Scen. 1.6	Scen. 1.7
1	-	4.00	3.00	-
2	0.22	-	0.22	0.70
3	0.22	-	0.22	0.70
4	0.22	-	0.22	0.70
All	**0.66**	**4.00**	**3.66**	**2.10**

6.2 Scenario 2 – Cafeteria on M/S Skåne

6.2.1 Design fire

The fire starts in the middle of the cafeteria, originating in a television set and spreading to nearby wooden structures (Figure 16).

Figure 16: TV-set placed on wooden structure.

The development of the heat release rates for TV's and particle boards are taken from separate experimental data and put together into one design fire peaking at 3200 kW after approximately 6 1/2 minutes /26/, see Appendix I. The effect of this design fire has been analyzed in a different geometry in chapter 0. The HRR is illustrated in Figure 17.

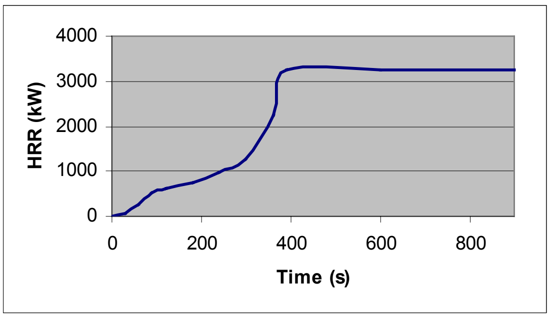


Figure 17: Heat release from a TV set.

6.2.2 Geometry

For the detailed scenario analysis the area that could be affected by a fire and the smoke it produces has been simplified. The total area, which possibly could become affected, is presented in Figure 18.

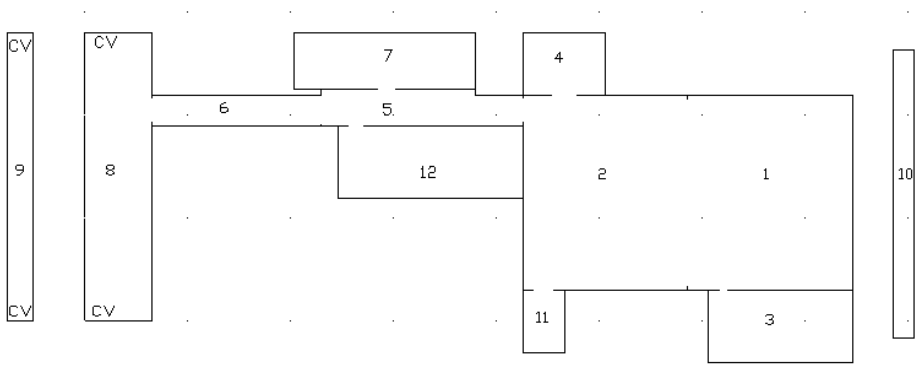
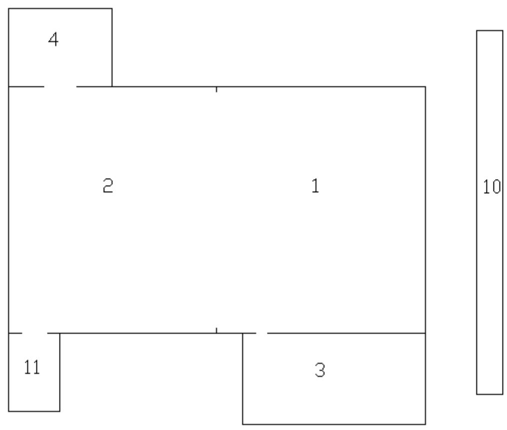


Figure 18: Area that could be affected by a fire.

By limiting the geometry to only incorporate compartments 1-4, 10 and 11 one can study the compartments most likely to be affected by the smoke produced. This limitation is based on the fact that the fire door between the arcade (comp. 5) and the cafeteria (comp. 2) will close in case of fire. The door will most probably stay closed since passenger evacuation through this door is not intended according to the safety plan and escape route plans of the ship. On the contrary, the fire doors to stairways 4 and 11 are assumed to be open due to passenger evacuation from the cafeteria. The simplified geometry for the computer simulations of Scenario 2 is presented in Figure 19. The ceiling height is 2.2 m for all compartments except stairways, 4.4 m.



The compartments are numbered from 1 to 12 representing:

1. Cafeteria, part I, fire comp. (19.0m×15.5m)
2. Cafeteria, part II (19.0m×15.5m)
3. Driver's dining room (15.5m×7.0m)
4. Stairway (6.0m×8.0m)

10. Hallway, on deck above – connected to compartments 4 and 11 (28.0m×2.0m)
11. Stairway (4.0m×6.0m)

Figure 19: Geometry for simulations in CFast.

6.2.3 Ventilation configuration

The different configurations for the simulation of the smoke control system are presented in Figure 20.

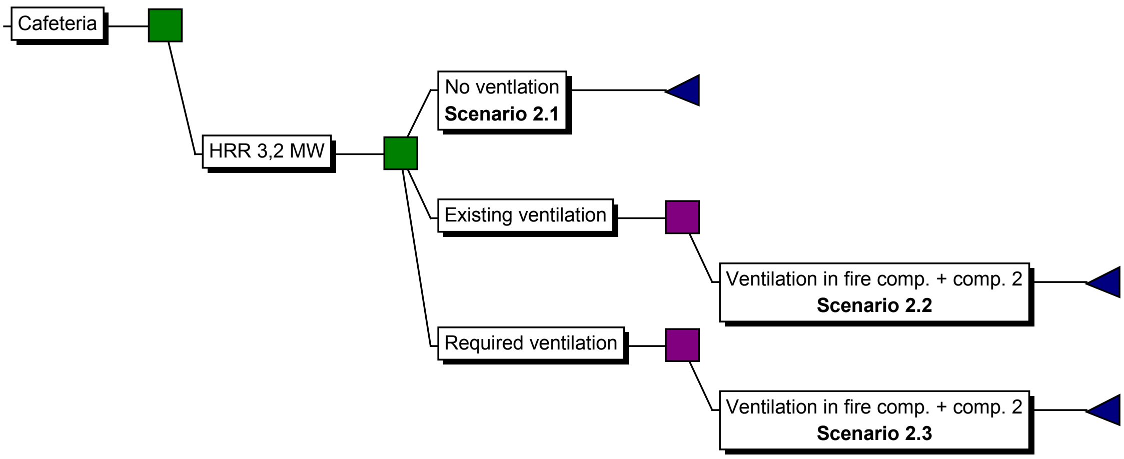


Figure 20: *Event-tree for the simulated scenarios (cafeteria).*

The existing HVAC ventilation system for the cafeteria is divided into four exhausts with a total capacity of 4.0 m^3/s. Since they all serve the same compartments the system was simplified to only incorporate two exhausts. In the simulations the exhausts were placed in compartments 1 and 2 with an equal capacity of 2.0 m^3/s for each compartment.

For the simulations of the required ventilation capacity the same configuration of exhausts as for the case with the existing HVAC was used. To secure tenable conditions according to BBR in the cafeteria and stairwells the capacity was set to 2.5 m^3/s for each compartment (1 and 2).

As discussed in chapter 5.3.1 the capacity used in this analysis is the design capacity, in this scenario 4.0 m^3/s. According to measured capacities of the HVAC-system on *M/S Skåne* the actual total capacity in the cafeteria is 5.9 m^3/s. This means that the HVAC-system in fact is sufficient to meet the criterions set for the design fire used.

The configuration and capacities of the smoke control system for existing and required ventilation is presented in Table 5.

Table 5: Distribution and capacities of exhaust ventilation for smoke control used in computer simulations.

Compartment #	**Existing ventilation capacity (m^3/s)**	**Required ventilation capacity (m^3/s)**
	Scenario 2.2	Scenario 2.3
1	2.0	2.5
2	2.0	2.5
All	**4.0**	**5.0**

6.3 Scenario 3 – Children's playroom on M/S Skåne

6.3.1 Design fire

Children playing with fire as well as the deed of an arsonist are the possible causes of this fire scenario. The children's playroom consists mainly of a pool of small plastic balls (Figure 21). Hand calculations to decide one probable and one maximum magnitude of the fire were carried out, see Appendix I.

To decide a probable HRR the fire was approximated as a polymer pool fire. The exact polymer, which the plastic balls in the pool are made up of, is not known but is approximated with the fire specific properties of PVC. The hand calculations resulted in a HRR of 1.65 MW.

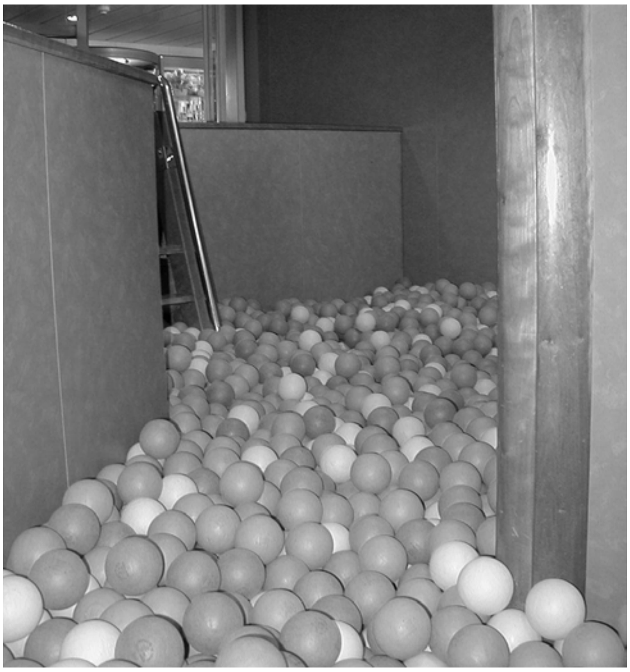
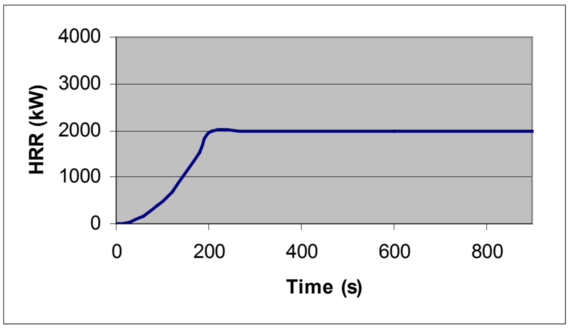


Figure 21: Plastic ball pool

The maximum HRR for the fire room was approximated with the equation based the opening factor /15/. This can be used based on simulation results saying there probably will be a flash over in the fire room (> 500 °C). The calculations resulted in a HRR of 2.9 MW.

The pool fire resulted in a heat release rate of 1.65 MW. Most likely will the fire will then spread to adjacent furniture, which will cause the fire to increase in intensity. To be conservative by the means of heat release rate and to treat the uncertainties a sensitivity analysis was made. This includes two peak heat release rates, 2 and 3 MW, and two different growth rates, corresponding to NFPA's Fast and Ultra Fast (Figure 22, 23, 24 and 25).



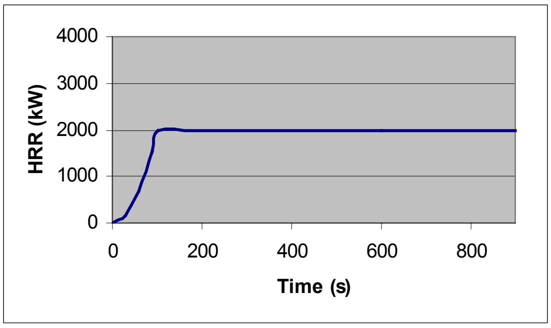
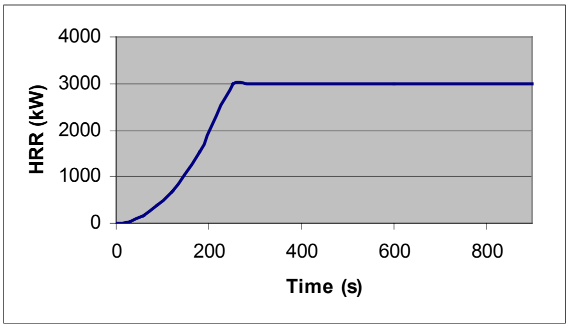


Figure 22:HRR of 2.0MW, growth rate Fast.

Figure 23: HRR of 2.0MW, growth rate Ultra Fast.



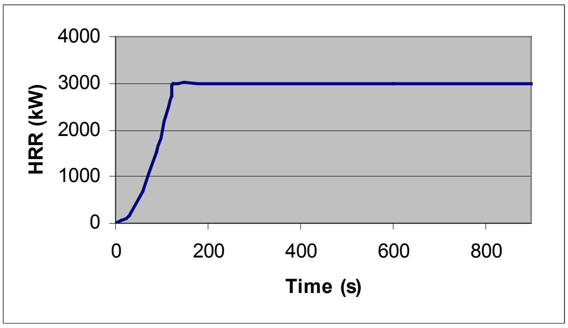


Figure 24: HRR of 3.0MW, growth rate Fast.

Figure 25: HRR of 3.0MW, growth rate Ultra Fast.

6.3.2 Geometry

For the detailed scenario analysis the area that could be affected by a fire and the smoke it produces has been simplified. The total area, which possibly could become affected, is presented in Figure 26.

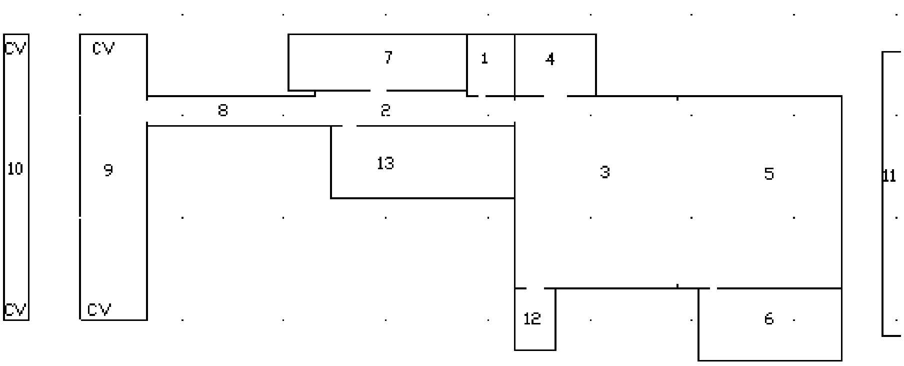
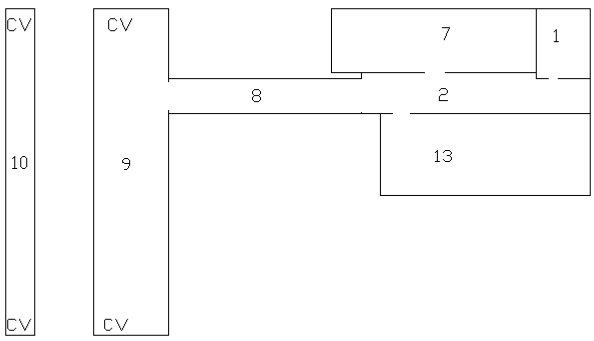


Figure 26: Area that could be affected by a fire.

By limiting the geometry to only incorporate compartments 1, 2, 7-10 and 13 (i.e. neglecting the cafeteria) one can study the compartments most likely to be affected by the smoke produced. This limitation is based on the same assumption as for Scenario 2: The fire door between the arcade (comp. 2) and the cafeteria (comp. 3) will close in case of fire and the door will most probably stay closed since passenger evacuation through this door is not probable due to the location of the fire, nor intended according to the safety plan and escape route plans of the ship. On the contrary, the fire door between the arcade (comp. 8) and the reception (comp. 9) is assumed to be open due to passenger evacuation from the arcade. On site studies showed that the doors to the air-seat lounge (comp. 7) and tax-free shop (comp. 13) were open during voyages, hence these are assumed to be incorporated in the smoke filling process.

The simplified geometry for the computer simulations of Scenario 3 is presented in Figure 27. The ceiling height is 2.2 m for all compartments.



The compartments are numbered from 1 to 13 representing:

1. Children's playroom, fire compartment (4.6m×6.0m)
2. Arcade, part I (3.5m×21.0m)
7. Air-seat lounge (5.5m×16.6m)
8. Arcade, part II (3.0m×16.5m)
9. Reception-hallway (6.5m×28.0m)
10. Hallway, on deck above – connected to compartment 9 (2.5m×28.0m)
13. Tax-free shop (7.0m×18.0m)

Figure 27: Geometry for simulations in CFast.

6.3.3 Ventilation configuration

The different configurations for the simulation of the smoke control system are presented in Figure 28.

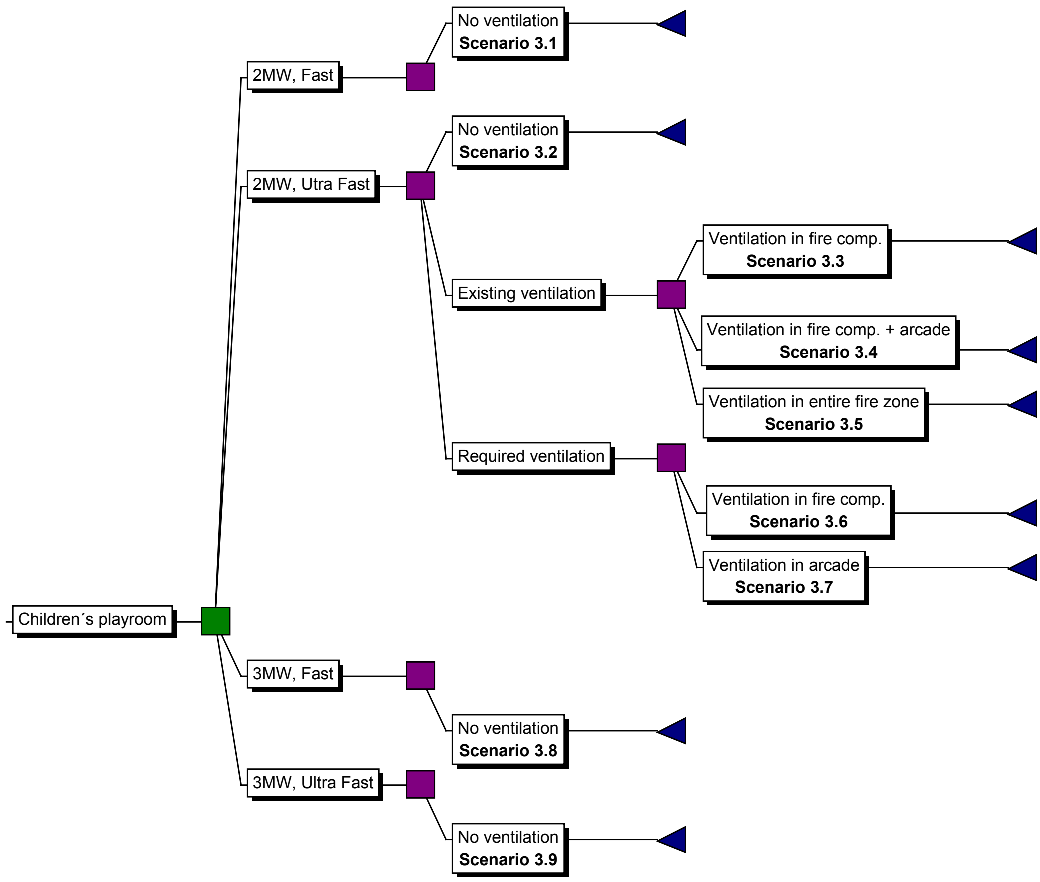


Figure 28: Event-tree for the simulated scenarios (children's playroom).

The existing HVAC ventilation system for the premises of the arcade is divided into numerous exhaust zones: One in the children's playroom (comp. 1), two in the air-seat lounge (comp. 7), two in the tax-free shop (comp. 13) and finally two in the arcade (comp. 2 and 8). In the computer simulations the two exhausts in compartments 7 and 13 were replaced with one, representing the total capacity of each compartment's exhaust. For the other compartments no additional changes were made.

To secure tenable conditions according to BBR the simulations of the required ventilation capacity were studied with two different solutions: One with the required capacity of 7.5 m^3/s for an exhaust in the fire compartment alone (comp. 1) and one with the required capacity of 2×4.0 m^3/s for exhausts in the arcade (comp. 2 and 8).

The configuration and capacities of the smoke control system for existing and required ventilation is presented in Table 6.

Table 6: Distribution and capacities of exhaust ventilation for smoke control used in computer simulations.

Compartment #	**Existing ventilation capacity (m^3/s)**			**Required ventilation capacity (m^3/s)**	
	Scen. 3.3	*Scen. 3.4*	*Scen. 3.5*	*Scen. 3.6*	*Scen. 3.7*
1	0.16	0.16	0.16	7.50	-
2	-	0.20	0.20	-	4.00
7	-	-	1.21	-	-
8	-	0.20	0.20	-	4.00
13	-	-	0.86	-	-
All	**0.16**	**0.56**	**2.63**	**7.50**	**8.00**

6.4 Scenario 4 – Cabin on M/s Alternative

6.4.1 Design fire

The analysed fire is one starting in one of the cabin beds, reasonably as a consequence of smoking or arson. The fire then spreads to adjacent beds reaching a total heat release rate (HRR) of approximately 1700 kW after 5 minutes. The interior in this cabin is assumed to be same as in scenario 1, thus the same development of the fire was chosen, Figure 29. This fire development is equivalent to experimental data.

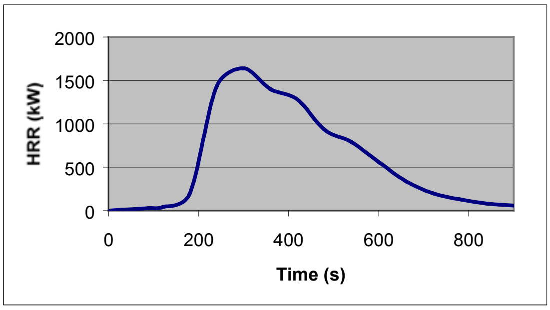
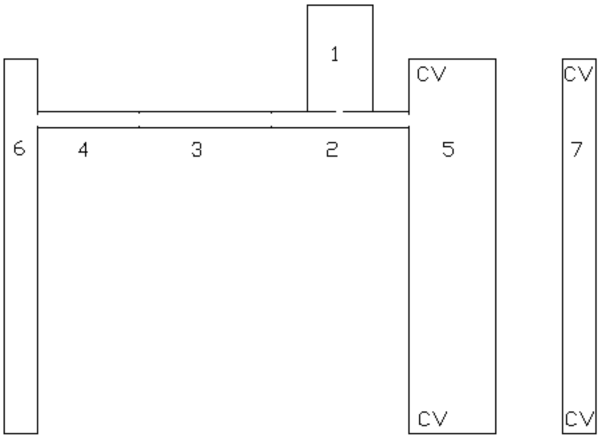


Figure 29: HRR with a decay phase

6.4.2 Geometry

The simplified geometry for the computer simulations of scenario 4 is presented in Figure 30. The ceiling height is 2.2 m for all compartments.



The compartments are numbered from 1 to 7 representing:

1. Cabin – fire compartment (6.0m×8.0 m).
2. Corridor, part I (10m×1.2m)
3. Corridor, part II (10m×1.2m)
4. Corridor, part III (7.5m×1.2m)
5. Reception – Hallway (28.0m×6.5m)
6. Hallway (28.0m×2.5m)
7. Hallway on deck above. Connected to compartment 5. (28.0m×2.5m)

Figure 30: Geometry for simulations in CFast.

The studied corridor has a total length of 27.5 m, and is divided into three parts by fire resistant doors. To increase the confidence level of the simulation results, the corridor outside the cabin was divided into three compartments (comp. 2, 3 and 4) in accordance with the placement of the doors. This separation was done mainly because of the limitations in CFast and since there is a natural compartmentation due to regulations /9/. The smoke will spread in a more realistic way with this separation.

6.4.3 Ventilation configuration

The different configurations for the simulation of the smoke control system are presented in Figure 31.

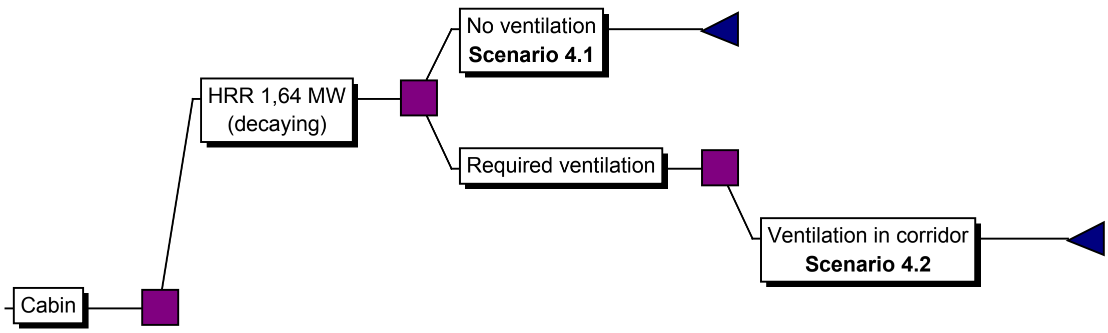


Figure 31: Event-tree for the simulated scenarios (cabin)

The existing HVAC system is assumed to have a capacity of 0.66 m^3/s, which is the same as on *M/S Skåne*. This assumption is based on the fact that larger cabins will need a higher ventilation capacity and since the number of cabins in the corridor on *M/S Skåne* will be twice as many as in a corridor with the same length on *M/S Alternative* the total capacity will be the same.

The required ventilation was simulated with one exhaust placed in each of the three corridor compartments (comp. 2, 3 and 4). Each exhaust was set to have a capacity of 1.0 m^3/s to secure tenable conditions in the corridor as well as in the hallway.

The configuration of the smoke control system for required ventilation capacity is presented in Table 7.

Table 7: Distribution and capacities of exhaust ventilation for smoke control used in computer simulations.

Compartment #	Required ventilation capacity (m^3/s)
2	1.0
3	1.0
4	1.0
All	**3.0**

6.5 Scenario 5 – Cafeteria on M/S Alternative

6.5.1 Design fire

The design fire is the same as for Scenario 2. The fire starts in the middle of the cafeteria, originating in a television set and spreading to nearby wooden structures. The development of the heat release rates for TV's and particle boards are taken from separate experimental data /25/ and put together into one design fire peaking at 3200 kW after approximately 6 1/2 minutes (Figure 32). The fact that the design fire is based on experimental data makes it possible to leave out the sensitivity analysis.

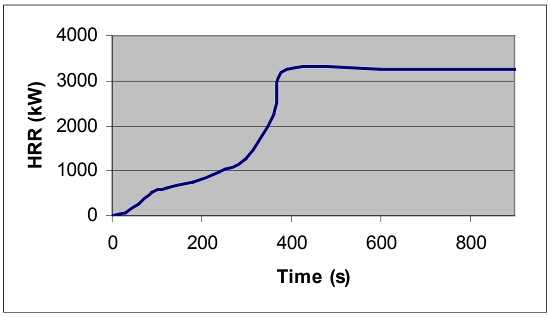
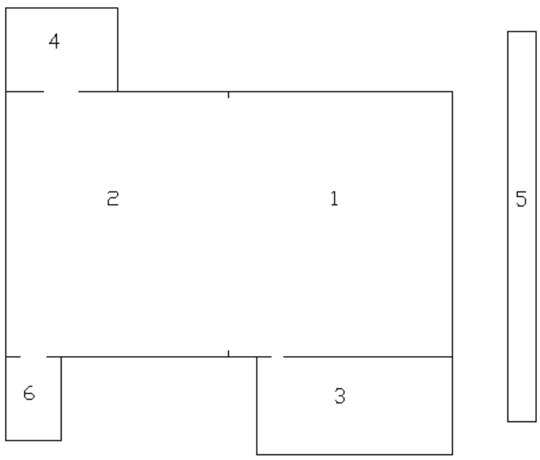


Figure 32: Heat release from a TV set

6.5.2 Geometry

The simplified geometry for the computer simulations of scenario 5 is presented in Figure 33. The ceiling height in compartment 1, 2, 4 and 6 is 4.4 m. Compartment 3 and 5, have a ceiling height of 2.2 m.



The compartments are numbered from 1 to 6 representing:

1. Cafeteria, part I, fire comp. (19.0m×15.5m)
2. Cafeteria, part II (19.0m×15.5m)
3. Driver's dining room (15.5m×7.0m)
4. Stairway (6.0m×8.0m)
5. Hallway, on deck above – connected to compartments 4 and 6 (28.0m×2.0m)
6. Stairway (4.0m×6.0m)

Figure 33: Geometry for simulations in CFast.

As in Scenario 2 (Cafeteria fire on M/S Skåne) the geometry has been simplified to include the cafeteria and a few additional compartments. Since the cafeteria is supposed to have the length of a fire zone, this zone is assumed to be evacuated separately and the doors to any adjoining compartment are therefore assumed to be closed. By this limitation one can study the compartments most likely to be affected by the smoke produced. Passengers in the cafeteria are to evacuate through stairways marked as compartments 4 and 6.

6.5.3 Ventilation configuration

The different configurations for the simulation of the smoke control system are presented in Figure 34.

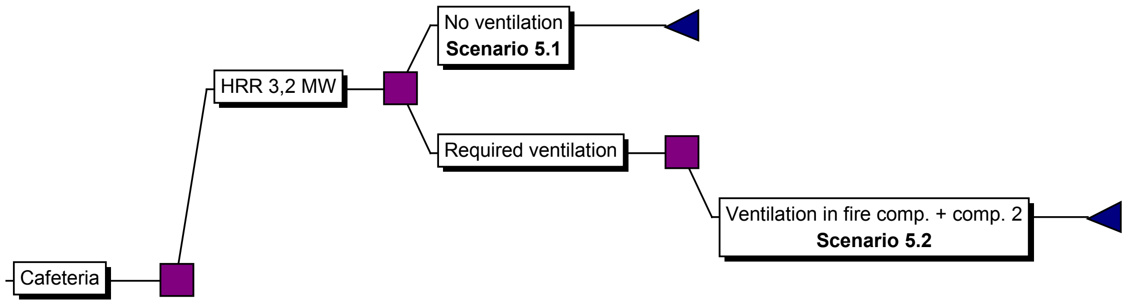


Figure 34: Event-tree for the simulated scenarios (cafeteria)

Due to the size of the cafeteria, the room was divided into two equal compartments (comp. 1 and comp. 2). In the simulations of the required ventilation, according to the criteria of tenable conditions in BBR, the exhausts were placed in compartments 1 and 2 with an equal capacity of 3.5 m^3/s each. This capacity secures tenable conditions in the cafeteria as well as in the stairwells.

The configuration of the smoke control system for required ventilation capacity is presented in Table 8.

Table 8: Distribution and capacities of exhaust ventilation for smoke control used in computer simulations.

Compartment #	**Required ventilation capacity (m^3/s)**
1	3.5
2	3.5
All	**7.0**

6.6 Scenario 6 – Assembly Hall on M/S Alternative

6.6.1 Design fire

The design fire has a development corresponding to NFPA's Fast with a peak heat release rate of 3.0 MW after approximately 4 minutes (Figure 35). This can be compared to a fire in two upholstered chairs /25/. Since the amount of interior varies from ship to ship, as well as the materials used, the magnitude of the fire has to be sensitivity analysed. As a result of this the maximum heat release rate is doubled to 6.0 MW, keeping the fast development, Figure 36, see Appendix I.

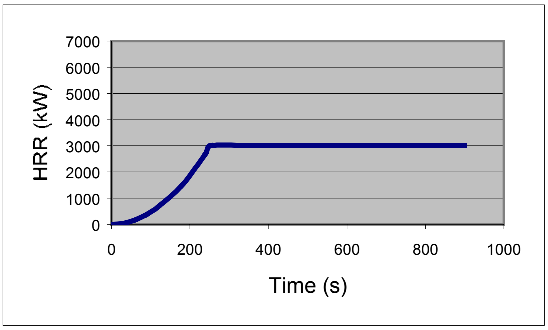


Figure 35: HRR of 3.0MW, growth rate Fast

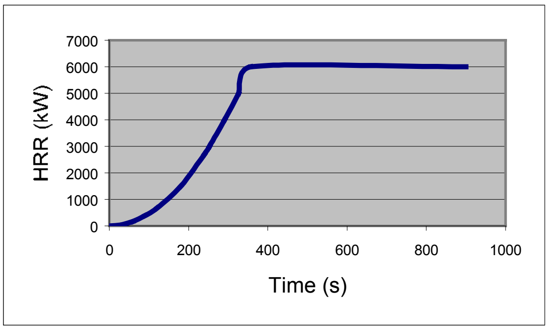
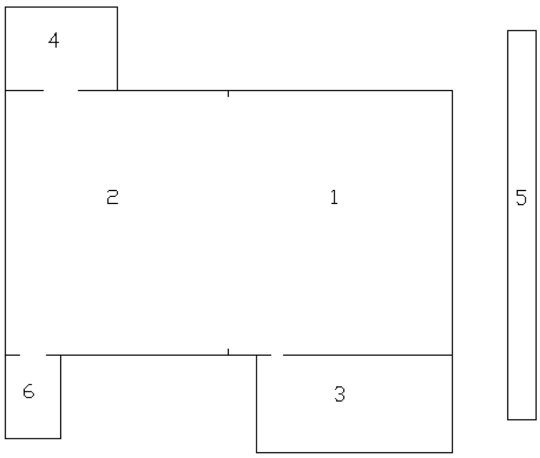


Figure 36: HRR of 6.0MW, growth rate Fast

6.6.2 Geometry

The simplified geometry for the computer simulations of scenario 5 is presented in Figure 37. The ceiling height in compartments 1 and 2 is 10.0 m. Compartments 4 and 6 has a ceiling height of 4.4 m and compartment 3 and 5 a ceiling height of 2.2 m.



The compartments are numbered from 1 to 6 representing:

1. Assembly hall, part I, fire compartment (19.0m×15.5m)
2. Assembly hall, part II (19.0m×15.5m)
3. Additional compartment (15.5m×7.0m)
4. Stairway (6.0m×8.0m)
5. Hallway, on deck above – connected to compartments 4 and 6 (28.0m×2.0m)
6. Stairway (4.0m×6.0m)

Figure 37: Geometry for simulations in CFast.

The geometry has been simplified to include the assembly hall and a few additional compartments. The assembly hall is supposed to have the length of a fire zone. This zone is assumed to be evacuated separately and the doors to any adjoining compartment are therefore assumed to be closed. By this limitation one can study the compartments most likely to be affected by the smoke produced. Passengers in the cafeteria are to evacuate through stairway 4 and 6.

6.6.3 Ventilation configuration

The different configurations for the simulation of the smoke control system are presented in Figure 38.

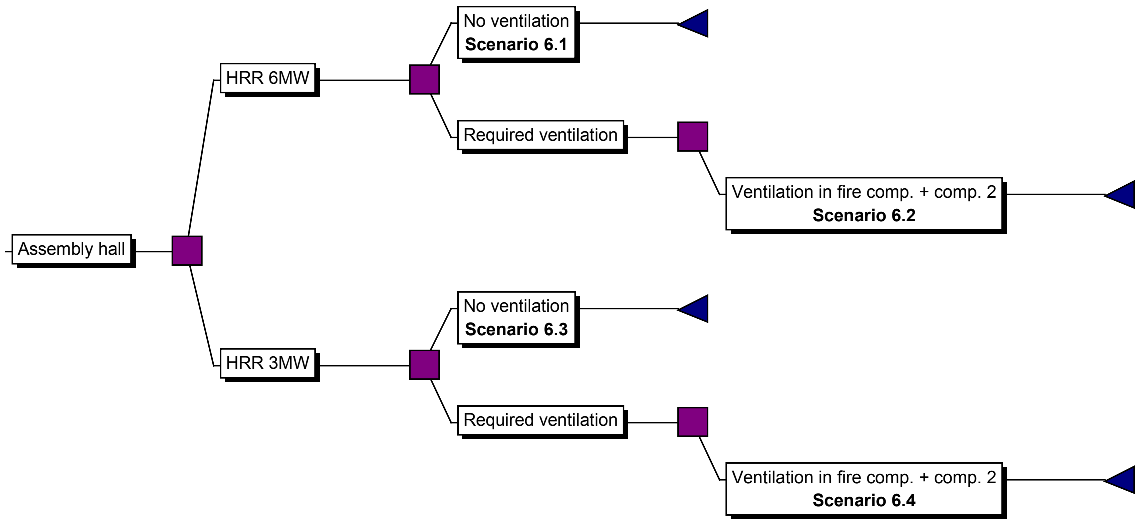


Figure 38: Event-tree for the simulated scenarios (assembly hall)

Because of the size of the assembly hall the total capacity of the required ventilation system was divided between compartment 1 and 2. One exhaust was placed in each compartment. To secure tenable conditions, according to the regulations in BBR, in the assembly hall and stairwells a capacity of 5.0 m^3/s (scenario 6.2) and 8.5 m^3/s (scenario 6.4) for each compartment (1 and 2) was needed.

The configuration of the smoke control system for required ventilation capacity is presented in Table 9.

Table 9: Distribution and capacities of exhaust ventilation for smoke control used in computer simulations.

Compartment #	**Required ventilation capacity (m^3/s)**	
	Scenario 6.2	Scenario 6.4
1	8.5	5.0
2	8.5	5.0
All	**17.0**	**10.0**

6.7 Scenario 7 – Atrium on M/S Alternative

6.7.1 Design fire

The design fire starts in the middle of the atrium in a similar way as the design fire in scenario 2. The fire originates in a television set and spreads to nearby wooden structures. The development of the heat release rates for TV's and particle boards are taken from separate experimental data /25/ and put together into one design fire peaking at 3.2 MW after approximately 6 1/2 minutes (Figure 39). Due to the large volume and different possible uses of an atrium this geometry requires a sensitivity analysis. The maximum heat release is therefore doubled, continuing from 3.2 MW to 6.4 MW with a growth rate corresponding to NFPA's Ultra Fast, see Appendix I. (Figure 40).

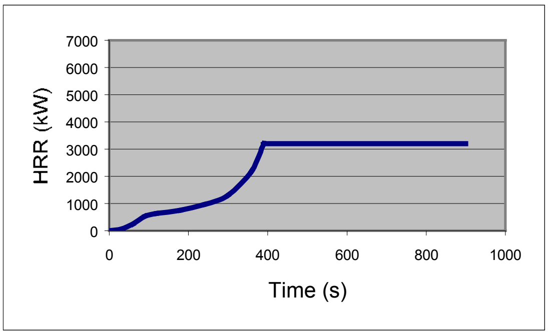


Figure 39: HRR of 3.2MW.

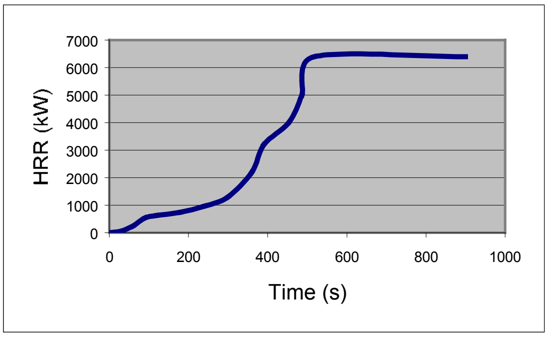
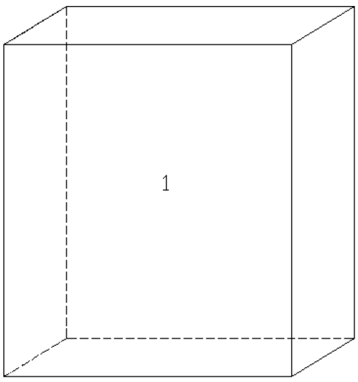


Figure 40: HRR of 6.4MW.

6.7.2 Geometry

The simplified geometry for the computer simulations of scenario 7 is presented in Figure 41.



Compartment 1 represents the atrium, and is also the fire compartment. The atrium measures 19.0m×15.5m and is 22.0m high.

Figure 41: Geometry for simulations in CFast.

6.7.3 Ventilation configuration

The different configurations for the simulation of the smoke control system are presented in Figure 42.

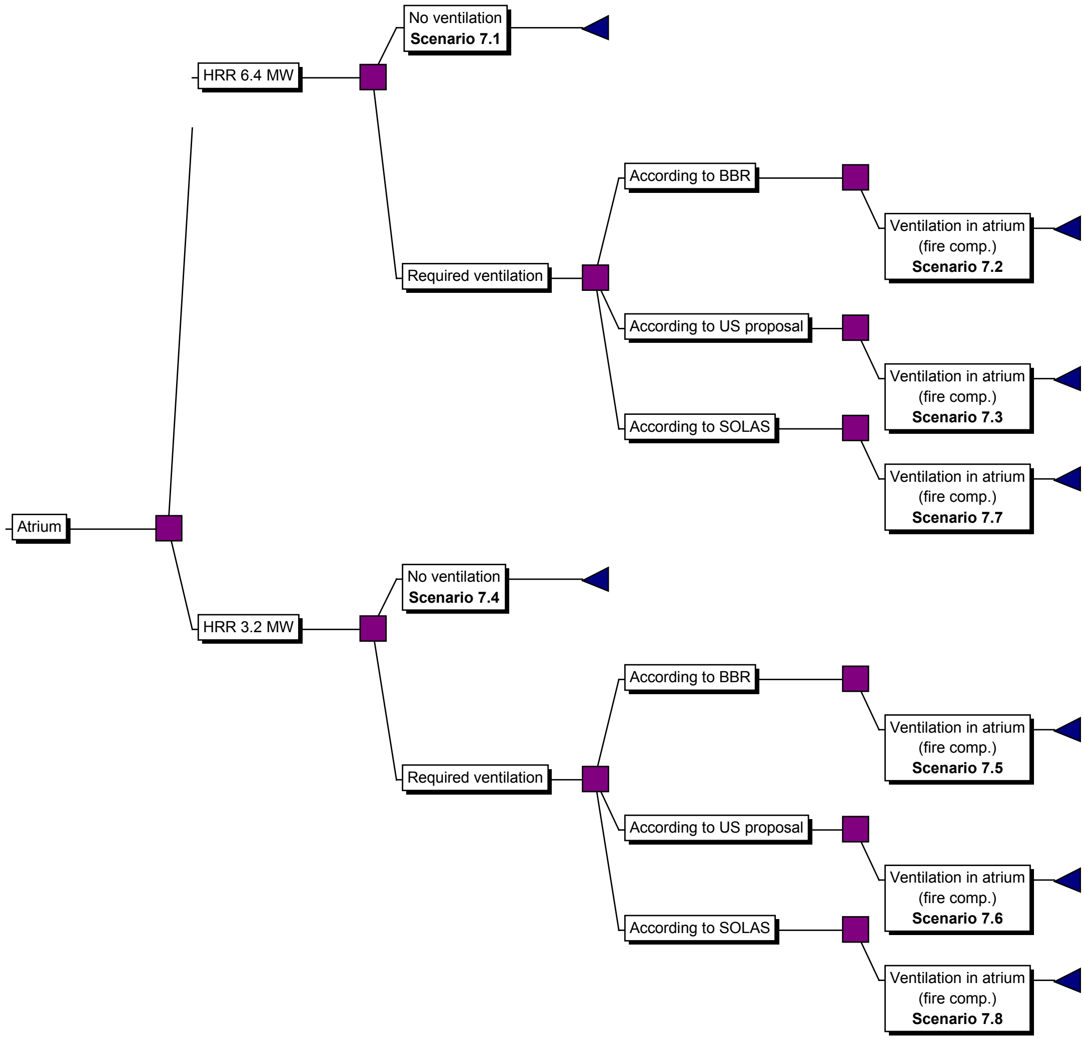


Figure 42 Event-tree for the simulated scenarios (atrium)

The size of the required ventilation capacity was determined on basis of the performance criteria in BBR and to the US proposals to SOLAS, see chapter 5.1. To secure tenable conditions in the atrium the required ventilation capacity varies between 12.5 m^3/s to 31 m^3/s.

The exhaust capacity requirement in SOLAS chapter II-2, stating that the entire volume of the atrium should be extracted within the time of 10 minutes is also compared to the BBR and US proposal criteria. For the atrium analysed, with a volume of 6479 m^3, the exhaust capacity would be 10.8 m^3/s, see Appendix I. This capacity is simulated both for the 6.4 MW fire (Scenario 7.7) and the 3.2 MW fire (Scenario 7.8).

The configuration of the smoke control system for required ventilation capacity is presented in Table 10.

Table 10: Distribution and capacities of exhaust ventilation for smoke control used in computer simulations.

Compartment #	**Required ventilation capacity (BBR/ US proposal) (m^3/s)**				**Required ventilation capacity (SOLAS) (m^3/s)**	
	Scenario 7.2	*Scenario 7.3*	*Scenario 7.5*	*Scenario 7.6*	*Scenario 7.7*	*Scenario 7.8*
1	22.0	31.0	12.5	21.0	10.8	10.8

7 Results from the quantitative risk analysis

The only results presented in this chapter are the smoke layer heights inside the fire compartment and the nearest adjoining compartments. These are the most interesting compartments to study since the further away from the fire compartment one gets, the more uncertain the output data becomes. A complete presentation of the smoke layer heights and temperatures for all compartment involved in the different scenarios is given in Appendix A - G.

7.1 Scenario 1 – Cabin on M/S Skåne

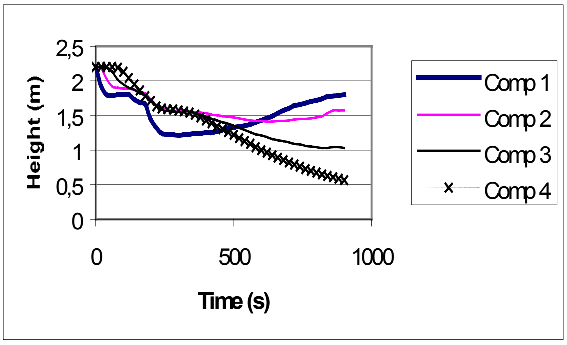
The results are evaluated on basis of the following acceptance criterion: Smoke free height of at least 1.8 m above deck within the time for evacuation, 900 s.

The design fire causes a flash over in the fire compartment (Comp 1) after about 3 ½ minutes making the two zone model inapplicable. Due to this the CFast results for this compartment should be interpreted with caution. The two-zone model applicability during the later phase of the fire is questionable for the adjacent hallways as well (compartments 5 and 7). This is due to low temperatures, causing limited buoyancy and hence no stratification in these compartments. The smoke filling process in compartments 5 and 7 will therefore only be commented briefly.

Since the design fire includes a decay phase the smoke layer rises towards the end of the simulation. This is due to the reduction of smoke production. The lowest level of the smoke layer during the simulation has been considered as the critical smoke height.

The simulations carried out can to some extent be compared to and verified by full-scale experiments /5/.

No ventilation:



With the HVAC-system completely shut down the smoke layer in the corridor descends to a critical level within 3 minutes. This is the case for adjoining areas as well.

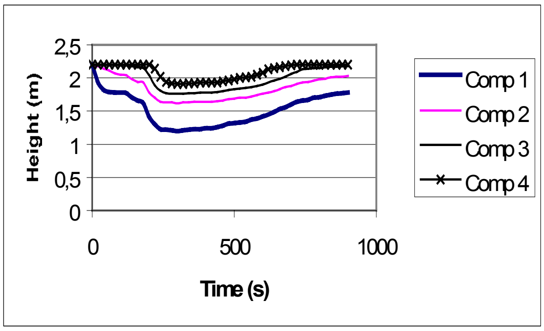
Figure 43: Scenario 1.1

Existing ventilation:
Three different configurations were analysed for the existing HVAC-system:

- Exhaust ventilation in fire compartment (comp. 1) of 0.0175 m^3/s (Scenario 1.2). The cabin exhaust has no evident effect on the smoke layer height. This scenario has been indirectly commented under Scenario 1.1 and will not be further analysed.

- Exhaust ventilation in fire compartment (comp. 1) and corridor (comp 2, 3 and 4) of 0.0175 m^3/s and 3×0.22 m^3/s respectively (Scenario 1.3). With the same assumption as for Scenario 1.2 the exhaust from the cabin will have a negligible effect on the smoke layer height. This makes the scenario equal to Scenario 1.4 below and thus not further analysed.

- Exhaust ventilation in corridor (comp. 2, 3 and 4) of 3×0.22 m^3/s (Scenario 1.4).

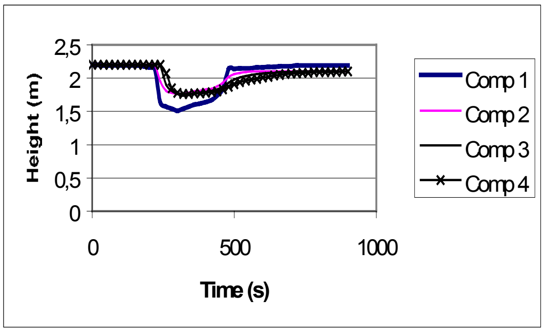


With the existing ventilation in the corridor running, tenable conditions are almost achieved. The worst conditions concerning temperature and smoke will occur in compartment 2 since this is the compartment closest to the fire. Here the smoke free height reaches a minimum level of 1.6 m.

Figure 44: Scenario 1.4

Required ventilation:
In a similar way as for the existing ventilation system, three different configurations were analysed for the required smoke control system:

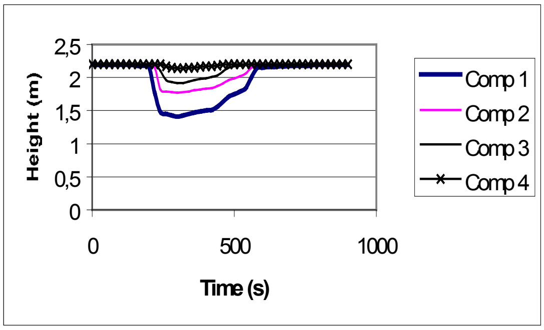
- Exhaust ventilation in fire compartment (comp. 1) of 4.0 m^3/s (Scenario 1.5).



With this solution the conditions in the corridor, as well as the adjoining hallways, can be considered acceptable. The smoke layer descends to the criterion level of 1.8 m.

Figure 45: Scenario 1.5

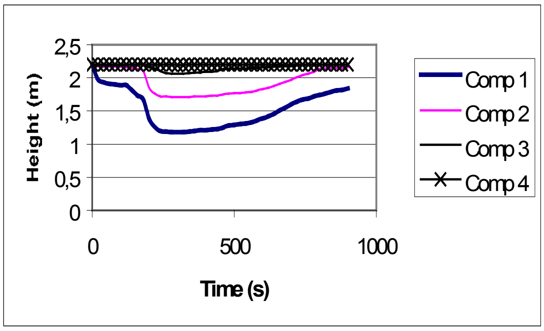
- An existing ventilation capacity of 3×0.22 m^3/s in the corridor (comp. 2, 3 and 4) requiring a capacity of at least 3.0 m^3/s in the fire compartment (comp. 1)(Scenario 1.6).



There is a considerable improvement when using the existing system exhausts in the corridor together with a more powerful smoke extraction in the cabin. The cabin exhaust can be reduced by 25 % compared to scenario 1.5. The smoke layer in the corridor and the adjacent hallways clearly descends to a lesser extent.

Figure 46: Scenario 1.6

- Exhaust ventilation in corridor of 3×0.70 m^3/s (Scenario 1.7).



This is a solution with the entire smoke extraction system concentrated to the corridor. With one exhaust in every corridor compartment (comp. 2, 3 and 4) the criterion is met for all escape ways, i.e. the corridor and the hallways.

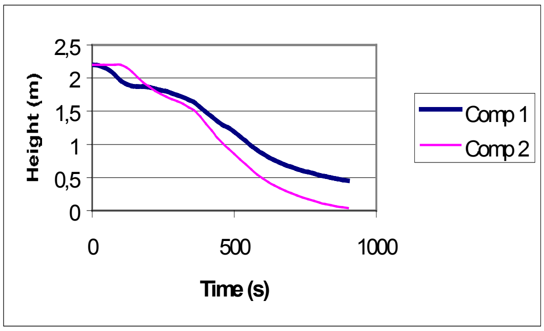
Figure 47: Scenario 1.7

7.2 Scenario 2 – Cafeteria on M/S Skåne

The results are evaluated on basis of the following acceptance criterion: Smoke free height of at least 1.8 m above deck within the time for evacuation, 900 s.

The cafeteria makes up a whole fire zone itself and therefore there are no separate escape routes. This is why the criterion is set for the cafeteria alone and the graphs only show the smoke filling process for these two compartments.

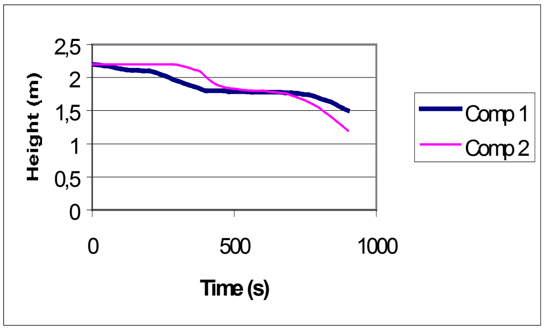
No ventilation:



This is the solution used today on M/S Skåne. It will lead to a complete smoke filling of the cafeteria. The acceptance criterion is exceeded within four minutes

Figure 48: Scenario 2.1

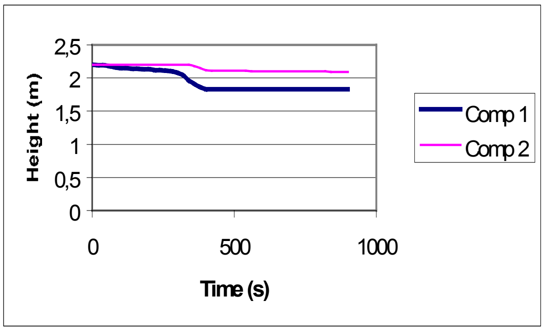
Existing ventilation:



The existing exhausts of the cafeteria have a total capacity of 4.0 m^3/s divided into two equal exhausts in the two cafeteria compartments. Running this system results in almost acceptable evacuation conditions but the smoke free height cannot be kept at 1.8 m.

Figure 49: Scenario 2.2

Required ventilation:



To achieve equilibrium between smoke produced by the fire and the smoke extracted the capacity of the smoke control system has to be at least 5.0 m^3/s. The exhausts are divided equally in the two cafeteria compartments. With this capacity the hot smoke layer stops descending at a level of 1.8 m after about 7 minutes.

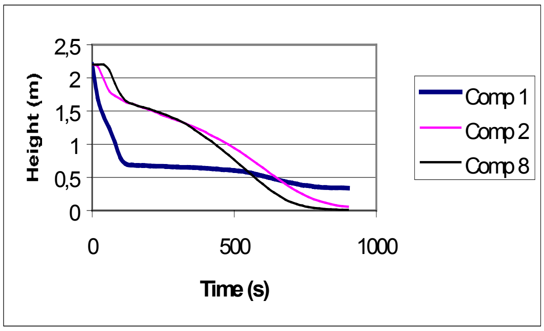
Figure 50: Scenario 2.3

7.3 Scenario 3 – Children's playroom on M/S Skåne

The results are evaluated on basis of the following acceptance criterion: Smoke free height of at least 1.8 m above deck within the time for evacuation, 900 s.

The design fire causes a flash over in the fire compartment (comp. 1) after about 3 ½ minutes, making the two-zone model inapplicable. Due to this the CFast results for this compartment should be interpreted with caution.

No ventilation:

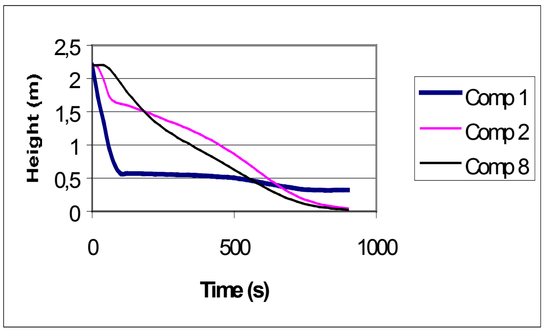


This solution, used today on M/S Skåne, will lead to a complete smoke filling of all escape routes, as well as all other compartments, within the analysed fire zone. The acceptance criterion for the arcade is exceeded within two minutes.

Figure 51: Scenario 3.1

Existing ventilation:
Three different configurations were analysed for the existing HVAC-system:

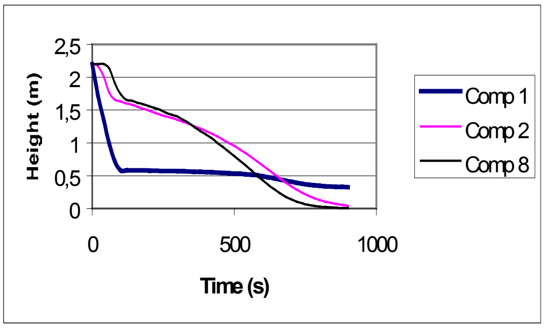
- Existing exhaust capacity in fire compartment (comp. 1) of 0.16 m^3/s (Scenario 3.3).



Running the exhaust fan in the fire compartment shows no obvious improvement of the conditions in compartment 2 and 8. This simply depends on the insufficient capacity of 0.16 m^3/s.

Figure 52: Scenario 3.3

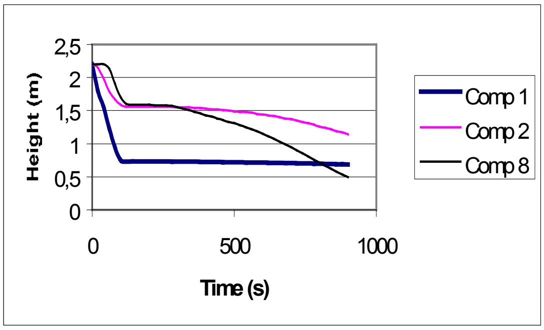
- Existing exhaust capacity in fire compartment (comp. 1) and arcade (comp. 2 and 8) of 0.16 m^3/s and 2×0.20 m^3/s respectively (Scenario 3.4).



When adding the exhausts in compartments 2 and 8, a minor improvement can be seen. Still, the total capacity of just 0.56 m^3/s is too small to keep the smoke layer above 1.8 m.

Figure 53: Scenario 3.4

- Existing exhaust capacity in fire compartment (comp. 1), arcade (comp. 2 and 8), lounge (comp. 7) and tax-free (comp. 13) of 0.16 m^3/s, 2×0.20 m^3/s, 1.21 m^3/s and 0.86 m^3/s respectively adding up to a total capacity of 2.63 m^3/s (Scenario 3.5).

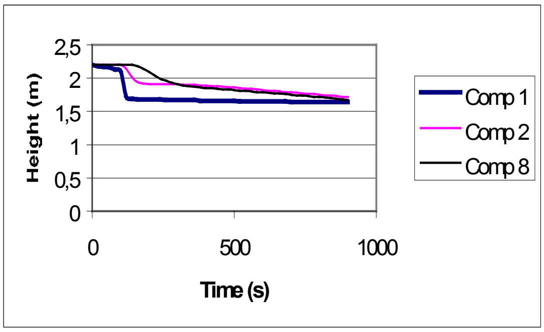


Running all exhausts in the fire zone affects the level of the smoke layer in a more distinct way. Even though the acceptance criterion is not fulfilled the conditions in the escape ways are practically tenable with a smoke free height of 1.5 m for almost 6 minutes.

Figure 54: Scenario 3.5

Required ventilation:

- Required exhaust capacity in fire compartment (comp. 1) of 7.5 m^3/s (Scenario 3.6).



One solution for the required ventilation is to place the exhausts in the fire compartment alone. Tenable conditions can be fulfilled but this requires a rather high capacity, 7.5 m^3/s, for a compartment of this size.

Figure 55: Scenario 3.6

- Required exhaust capacity in arcade (comp. 2 and 8) of 2×4.0 m³/s (Scenario 3.7).

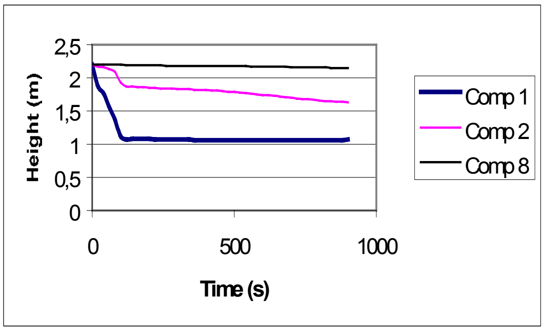


Figure 56: Scenario 3.7

Another solution for the smoke control system is to extract smoke through the exhausts in the escape ways alone (Scenario 3.7). With a total exhaust capacity of 8.0 m^3/s equally distributed in the arcade the conditions meet the criterion of 1.8 m.

7.4 Scenario 4 – Cabin M/S Alternative

The results are evaluated on basis of the following acceptance criterion: Smoke free height of at least 1.8 m above deck within the time for evacuation, 900 s.

Since the design fire includes a decay phase the smoke layer rises towards the end of the simulation. This is due to the reduction of smoke production. The lowest level of the smoke layer during the simulation has been considered as the critical smoke height.

No ventilation:

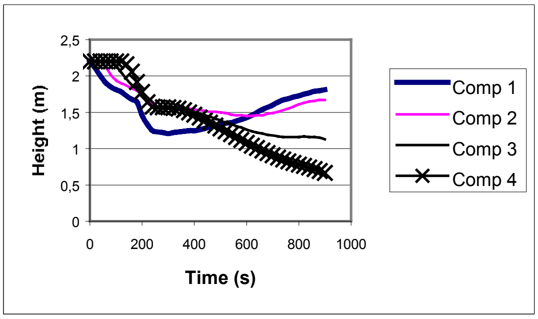


Figure 57: Scenario 4.1

With the ventilation shut down the smoke rapidly descends below the acceptance criterion. Since the design fire has a decay phase the smoke production decreases with time and the smoke layer therefore rises some at the end of the simulation. The smoke will then spread to adjoining compartments, but will be more and more diluted. At 3 minutes the acceptance criterion in the corridor is exceeded.

Required ventilation:

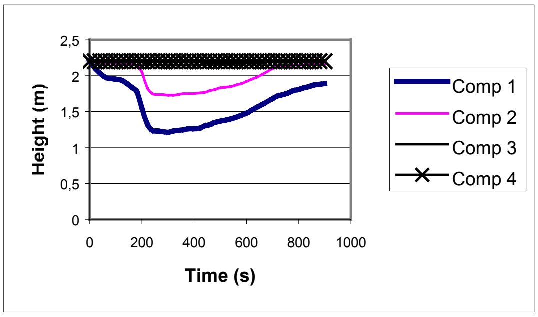


Figure 58: Scenario 4.2

The capacity required for a smoke control system with exhausts in the corridor alone is at least 3×1.0 m^3/s. With this capacity tenable conditions can be reached for the corridor as well as the adjoining escape ways. The smoke free height reaches its minimum after 5 minutes in comp. 2, stabilises for a few minutes and then rises again.

7.5 Scenario 5 – Cafeteria M/S Alternative

The results are evaluated on basis of the following acceptance criterion: Smoke free height of at least 2.0 m above deck within the time for evacuation, 900 s.

No ventilation:

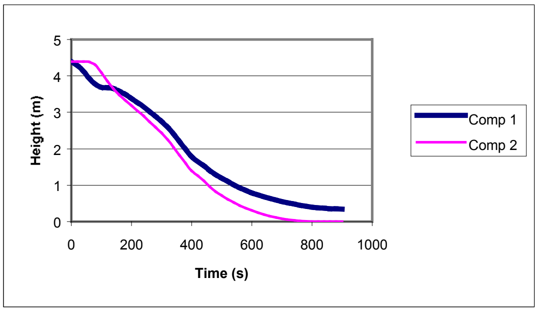


Figure 59: Scenario 5.1

Without a smoke control system the conditions in the cafeteria become critical within 6 minutes. At this time the smoke can also spread to adjoining compartments or fire zones if any door has been left open during the evacuation procedure.

Required ventilation:

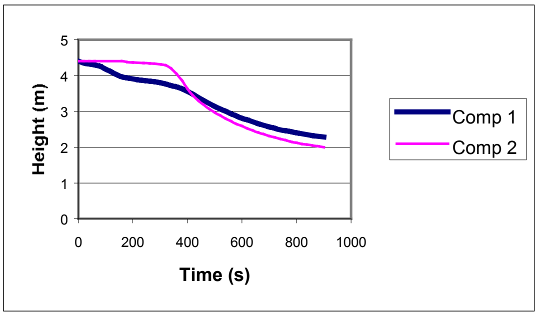


Figure 60: Scenario 5.2

The capacity of the smoke control system in the cafeteria has to be at least 2×3.5 m^3/s to keep the smoke layer above the critical height. Since the critical smoke layer height, 2.0 m, is lower than the door heights, 2.1 m, the smoke can continue to spread to other compartments; for example the stairways. Due to this the capacity of 2×3.5 m^3/s is an absolute minimum for this geometry.

7.6 Scenario 6 – Assembly Hall M/S Alternative

The results are evaluated on basis of the following acceptance criterion: Smoke free height of at least 2.6 m above deck within the time for evacuation, 900 s.

No ventilation:

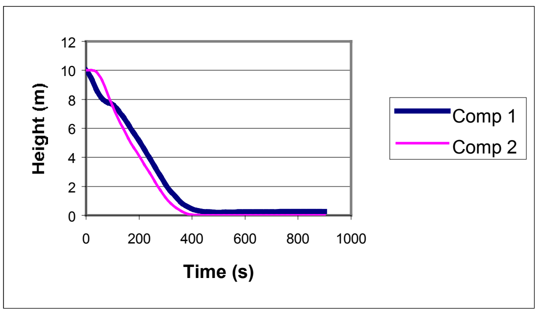
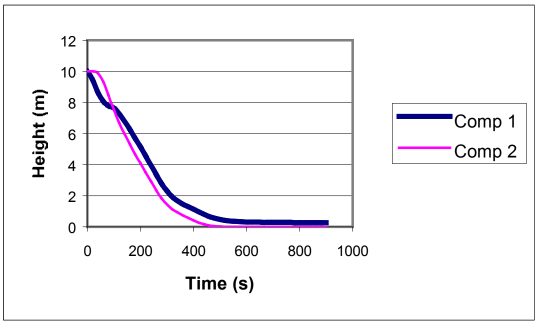


Figure 61: Scenario 6.1

Without running the ventilation system, the smoke will reach a critical height after about 4 minutes. Smoke spread to adjoining compartments due to open doors will possibly occur after 4 ½ minutes.

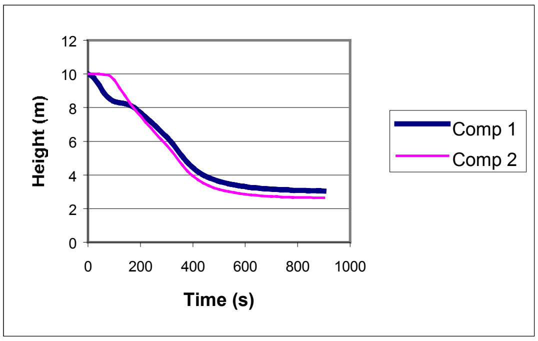


The smoke filling process will be similar up to the time of 4 minutes for both Scenario 6.1 and 6.3, but as the fire in Scenario 6.1 continues to develop to twice the HRR of Scenario 6.3 the smoke will be much thicker and warmer.

Figure 62: Scenario 6.3

Required ventilation:

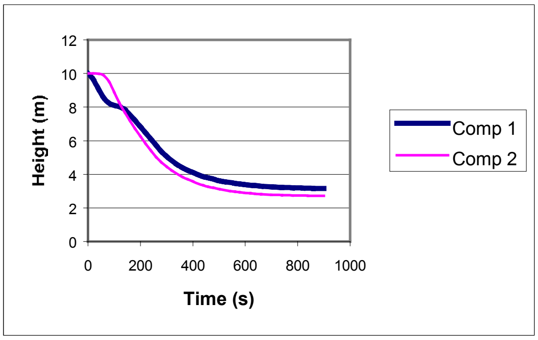
- Required exhaust capacity of 2×8.5 m^3/s (Scenario 6.2)



To meet the criterion for the assembly hall the smoke control system need a total capacity of 17.0 m^3/s for a 6.0 MW fire. A system of this size also prevents smoke from spreading to adjoining compartments.

Figure 63: Scenario 6.2

- Required exhaust capacity of 2×5.0 m^3/s (Scenario 6.4)



For the 3.0 MW fire the required capacity of the smoke control system will be 10.0 m^3/s totally. As for Scenario 6.2 the spread of smoke to the surrounding compartments can be avoided.

Figure 64: Scenario 6.4

7.7 Scenario 7 – Atrium M/S Alternative

The results are evaluated on basis of two different criterions:

1. BBR: Smoke free height of at least 3.8 m above the atrium floor within the time for evacuation, 900 s (Scenario 7.2 and 7.5).
2. US proposal: Smoke free height of at least 1.8 m above the upper most deck within the time for evacuation, 900 s. This is equivalent to a total smoke free height of 21.8 m measured from the lowest deck (Scenario 7.3 and 7.6).

No ventilation:

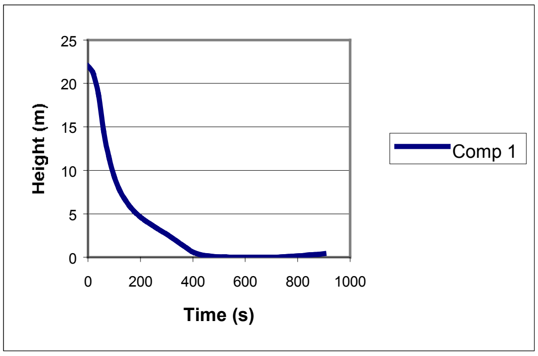


Figure 65: Scenario 7.1

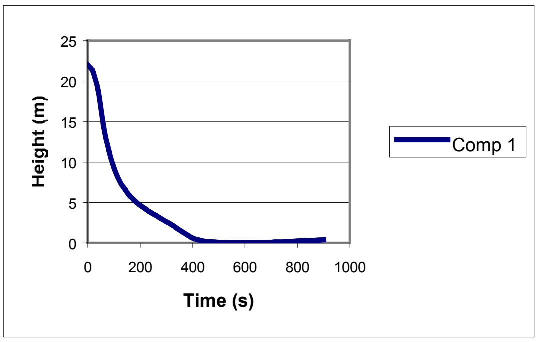


Figure 66: Scenario 7.4

For the two design fires in the atrium the acceptance criterion will be exceeded in about 4 minutes when not running any system for smoke extraction. After 7 minutes the atrium will be completely filled with smoke, with higher temperature and obscurity for the 6.4 MW fire (Scenario 7.1) than for the 3.2 MW fire (Scenario 7.4).

Required ventilation:
Six different scenarios have been analysed to find the different required capacities of the smoke control system in the atrium:

- Required exhaust capacity of 22.0 m^3/s (Scenario 7.2)

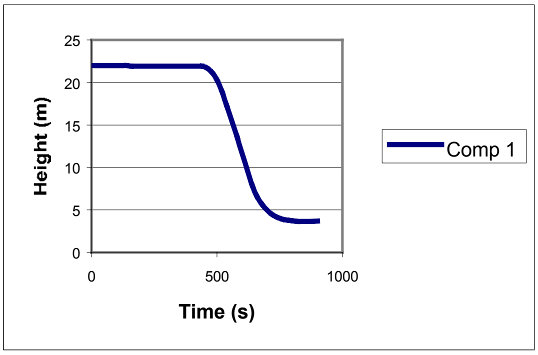
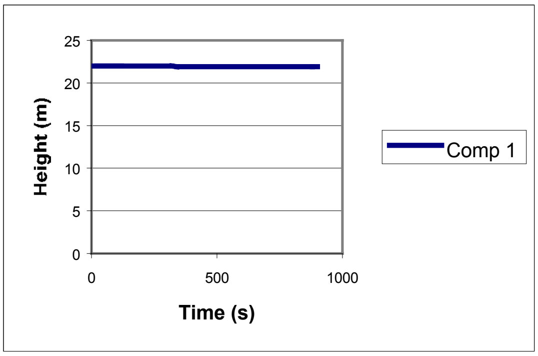


Figure 67: Scenario 7.2

To meet the acceptance criterion of 3.8 m, the exhaust capacity required for the atrium is 22.0 m^3/s. When activated immediately this will keep the atrium completely free from smoke during the first eight minutes, but as the temperature rises the hot gases expand. Larger gas volumes demand larger extraction capacity and this causes the smoke layer to descend. But as the smoke layer descends and the smoke at the same time is extracted, the average temperature starts to fall leading to a state of equilibrium at around 3.8 m above deck. (The temperature graph can be viewed in Appendix G.)

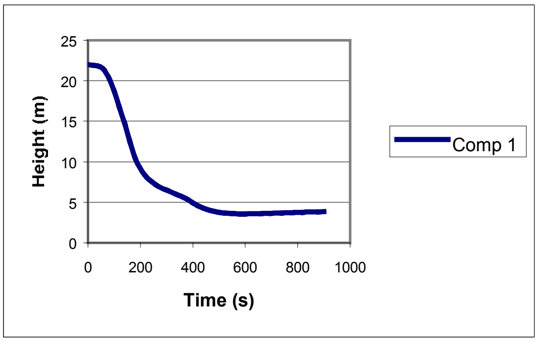
- Required exhaust capacity of 31.0 m^3/s (Scenario 7.3)



To be able to keep the upper most deck free from smoke for this design fire, a capacity of at least 31.0 m^3/s is needed for the smoke control system. By meeting this criterion the prevention of any smoke from spreading to adjoining compartments is made.

Figure 68: Scenario 7.3

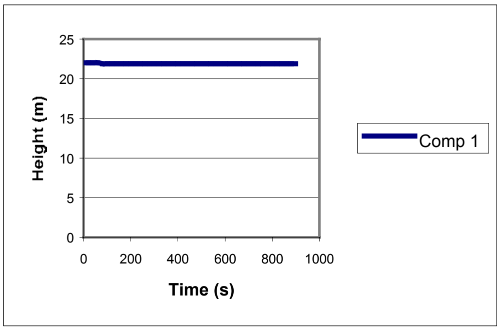
- Required exhaust capacity of 12.5 m^3/s (Scenario 7.5)



For the smaller design fire a smoke control system with an exhaust capacity of at least 12.5 m^3/s will be needed to meet the acceptance criterion of 3.8 m.

Figure 69: Scenario 7.5

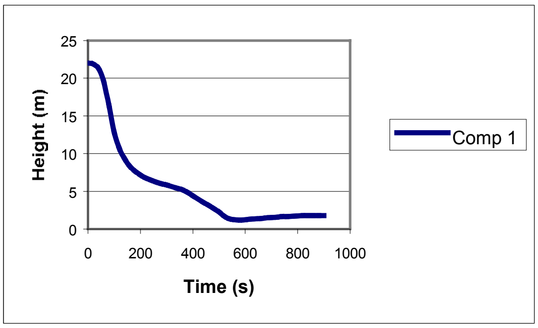
- Required exhaust capacity of 21.0 m^3/s (Scenario 7.6)



Keeping the upper most deck free from smoke for this design fire requires a smoke extraction system with the capacity of at least 21.0 m^3/s. As for Scenario 7.3 further smoke spread will be prevented.

Figure 70: Scenario 7.6

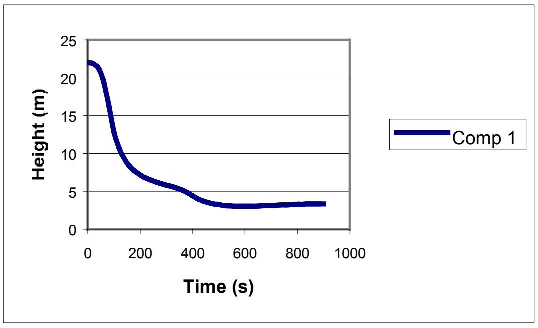
- Required capacity to exhaust entire volume in 10 minutes for a 6.4 MW fire (Scenario 7.7). The capacity is 10.8 m^3/s.



For the larger fire, the smoke layer descends as low as 1.2 m above deck, clearly showing the insufficiency of the system as both the criteria set are exceeded.

Figure 71: Scenario 7.7

- Required capacity to exhaust entire volume in 10 minutes for a 3.2 MW fire (Scenario 7.8). The capacity is 10.8 m^3/s.



For this fire, the simulation of a system designed to exhaust the entire volume of the atrium in 10 minutes results in a smoke free height of 3.0 m. This is not in accordance with any of the criteria set for the atrium.

Figure 72: Scenario 7.8

8 Conclusions

To be able to draw conclusions from the results of this study, the qualitative discussion carried out in chapter 3 and 4 had to be added to the quantitative part of the risk analysis, presented in chapter 6 and 7. The conclusions are thereby based not only on the simulations and computations carried out, but they are also supported by proposed expert solutions and opinions.

This chapter has a somewhat different outline then chapter 6 and 7. The conclusions are first drawn in a general manner, chapter 8.1, and are then divided into conclusions drawn for more specified accommodation areas. These are:

- *Cabin areas*, Scenario 1 and 4, chapter 8.2.
- *Large public spaces,* Scenario 2, 5 and 6, chapter 8.3.
- *Arcades – small public spaces*, Scenario 3, chapter 8.4.
- *Atriums*, Scenario 7, chapter 8.5.

8.1 General conclusions

These conclusions are general for all scenarios:

- When designing a smoke control system one should use a certain criterion by the means of smoke free height in evacuation routes and communicating spaces leading to these, and not a criterion fixed to the volume of the space. The latter do not account for the fire load of the specific space, nor the geometry by the means of location of evacuation routes.

- An "emergency shut down" of the HVAC system, in the purpose to prevent smoke spread does not necessarily have to improve the evacuation conditions. **If one continues to run the system in the affected fire zone the conditions only become better,** presupposed that recirculation of the extracted air is prevented by dampers. In earlier research this has been verified by full-scale tests /5/.

- **Over-pressurisation of adjoining fire zones** prevents or limits the smoke spread to these zones. This is especially important when evacuation has to take place through another fire zone causing doors to be open. The over-pressurisation can be managed with some sort of "Smoke Control Strategy".

- A smoke control system causes a pressure gradient inside the area it is operating. One therefore has to **pay special attention to the doors placed in the escape ways**. To open a door, one should only need a maximum force of 130 N, according to the regulations by for example NFPA and BBR. Maybe this value is recommendable for SOLAS too? Further research has to be made though. Another alternative, which also has to be evaluated further, is whether or not to **change the opening direction** of the escape way doors.

- Exhausts should be **located at ceiling height** to have the best effect. This since the hot gases are concentrated at ceiling level. A high location decreases the amount of fresh air extracted.

- Important is to make sure that the system is **resistant to hot smoke** during a certain time (normally the fire resistance time for the fire zone.) The fans have to be fully operable during this time. The risk for sparks igniting uncombusted gases also has to be considered.

- One has to make sure that the smoke control system installed **prevents smoke spread** to other parts of the ship through the system. As an example one has to have at least one separate system for each fire zone. If the system incorporates more than one fire zone, the system has to be isolated and dampers should be used where needed.

8.2 Cabin area

The following conclusions can be drawn:

- It is necessary to install a separate smoke control system in the cabin area if not a higher capacity HVAC-system can be used.

- The smoke control system is to be designed for a design fire where, among others, parameters like fire load and cabin size will affect the smoke production. A comparison between Scenario 1 and Scenario 4 shows that cabin size may affect the amount of smoke being produced and hence the extraction rate of the smoke control system. With a cabin size in Scenario 4 of 6.0m×8.0m the total smoke exhaust capacity required is 3.0 m^3/s. For Scenario 1, with cabins of 3.0m×4.0m the required capacity is only 2.1 m^3/s, see table below.

- The exhaust should be placed in the corridor, preferably equally distributed. A separate smoke control system in each cabin is not to recommend. According to Scenario 1, extraction in each cabin requires a capacity of 4 m^3/s. A system with this capacity would take up a lot of space and generate unnecessary installation costs.

- Supply air should as a rule be taken from the cabins existing supply air system. If this capacity is not enough one can complement the amount of supply air with air from adjoining stairways if these are over-pressurised. An example of this is if the doors between the cabin area and the stairways are kept open when the system is operating. This situation is very likely to appear during an evacuation procedure.

8.3 Large public spaces

The meeting of the criterion for the smoke layer height and the comfort requirement of 12 changes/h seems to have an analogous relation for larger public spaces, atriums with some exceptions though, see chapter 8.5. A comparison with the geometries on *M/S Alternative* (Scenario 5 and 6) shows that this requirement (12 changes/h) on the HVAC-system even results in capacities higher than the ones necessary to keep the smoke layer at the critical height (see table below).

Type of system	Capacity (m^3/s)		
	Cafeteria Scenario 2	**Cafeteria Scenario 5**	**Assembly Hall Scenario 6**
HVAC-system according to drawings[1] or with 12 changes/h[2]	4.0-5.0[1]	8.6[2]	19.6[2]
Smoke control system with required capacity	5.0	7.0	17 (6MW) 10 (3MW)

The following conclusions can be drawn:

- If the HVAC-system in public areas is designed to provide 12 changes/h, the system can be said have enough capacity to be used as a smoke control system.

- One neither needs more powerful fans nor larger dimensions on the ducts since these are designed for large capacities anyway.

- This motivates the idea to design HVAC-systems for these areas in a fashion that they can operate as smoke control systems as well. This should be considered both when installing a new system or upgrading an existing one.

This can be said on basis of the analysed geometries and is valid for larger public areas. An exception for this is smaller public compartments were the fire load is considered to be high (see chapter 6.3, 7.3 and 8.4).

8.4 Arcades – small public spaces

The following conclusions can be drawn:

- The HVAC system installed in a public area cannot straight off be considered to have the capacity of a smoke control system. In contrast to the larger public spaces this typical example has a capacity that is far below the required. Hence, every system has to be designed on basis of a specific design fire.

- How does one design a smoke control system in an area like this arcade? The purpose is to meet the criterion for critical conditions in the escape ways, in this case the arcade, during the time for the evacuation. The recommended solution is to place the smoke control extractions in the arcade, as they were placed in the corridor in the cabin area (Scenario 1 and 4). This solution should be used since the tax-free shop and the lounges are considered to be rather small compartments. It is not reasonable to place a separate smoke control system in each of these rooms. Obviously this depends on the specific geometry, but works out very well on *M/S Skåne*.

- Another solution for these compartments is to **limit the amount of fire load**. This would lead to a smaller design fire, which requires a lower extraction capacity to meet the criterion.

8.5 Atrium

The following conclusions can be drawn:

- The existing regulations in SOLAS does not require sufficient capacity of the smoke control systems in order to fulfil the acceptance criteria used in this report. The applicability of the SOLAS requirement is limited since no consideration is taken to different fire load (design fire size) and the requirement that the smoke layer should be kept at a safe level above deck in all evacuation routes, independent of their level in the atrium.

- Regulations for smoke control should use the height to the smoke layer as acceptance criterion and not a criterion fixed to the volume of the atrium.

- The normal HVAC-system is in most of the cases studied almost sufficient and consequently it is relatively easy to upgrade it to a smoke control system.

- Achieving a smoke free height of 1.8 m at the upper most deck in the atrium is the most demanding requirement. In the simulations this lead to rather high extraction capacities compared to those provided by a 12 changes/h HVAC-system. This would mean somewhat higher installation costs and some loss of space due to larger ducts. It might instead be more appropriate to allow the smoke to descend to a lower level in the atrium and to prevent the smoke from spreading to adjacent spaces by other means, for example by smoke tight barriers.

9 Further work

As this project has progressed, a number of parameters have been identified that influence a smoke control system. The importance of and the significance of some of these parameters are however not thoroughly investigated and further research is needed in certain areas in order to achieve more reliable results. Below is listed a number of suggested areas to further investigate in the future.

- Another computer program should be used as a complement and verification of the results given from CFast. To verify the two-zone model a CFD-model (Computational Fluid Dynamics) would be a good alternative. The CFD-model is more capable to handle smoke spread and the situation of a flashover, which probably will appear in the case of a cabin fire.

- The effects of winds have not been analyzed in a quantitative way. An interesting research project of tomorrow would be to investigate the influences of external wind on a smoke control system.

- This report contains an extensive analysis of the pros and cons with a smoke control system. It has been shown that a smoke control system will have a positive effect on the means of egress. Different ventilation configurations have been simulated in this report, but no detailed analysis of which configuration is the most effective one has been done.

- It is known that a sprinkler system has a very good suppression effect on a fire. This report has shown that a smoke control system has very good effect on the means off egress. It would be very interesting to be able to simulate the interaction of a sprinkler system and a smoke control system.

- Even though some full-scale experiments have been done, more experiments would give an improved knowledge of which effects a smoke control system has. The experiments carried out this far have only included the cabin area. It would be interesting to see if there are any restrictions that have not been considered in other areas, i.e. restaurants, assembly halls and atria.

- Performance criteria have not yet been established for the new SOLAS and this report only carry out a discussion on what criteria is to be used. A more detailed study is recommended to determine the criteria applicable on ships.

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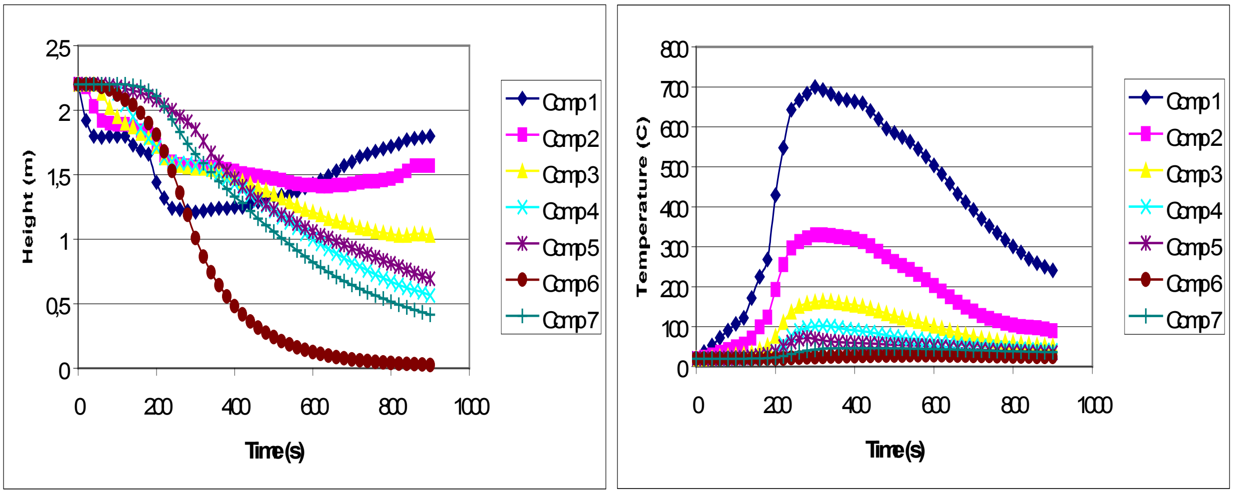
Appendix A

Computer simulations of Cabin

M/S Skåne

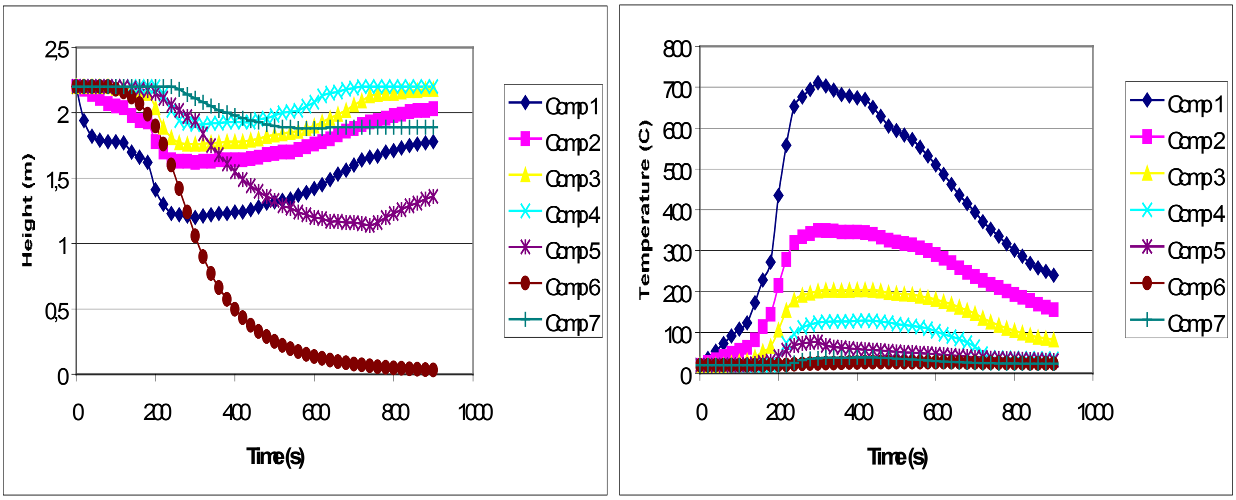
Scenario 1.1

M/S Skåne, Cabin, Decaying HRR, No ventilation



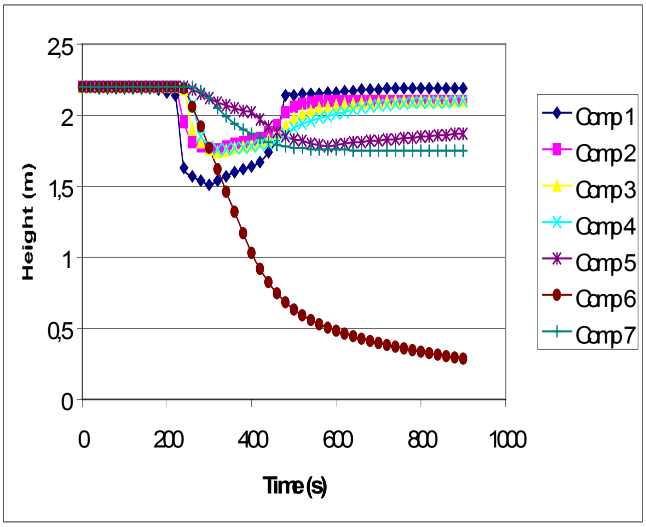
Scenario 1.4

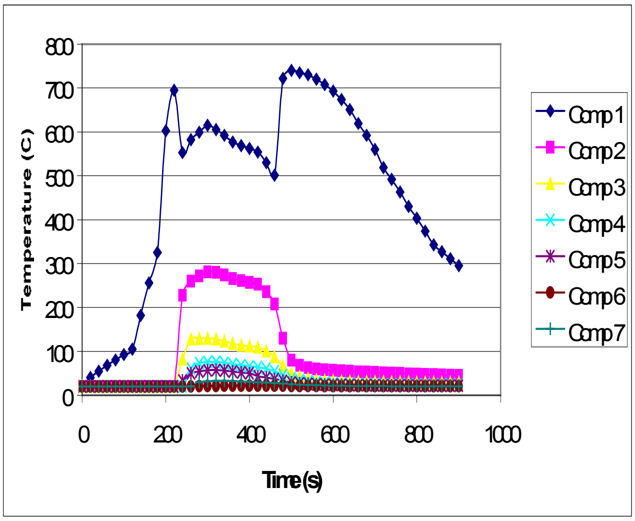
M/S Skåne, Cabin, Decaying HRR, Existing ventilation in corridor



Scenario 1.5

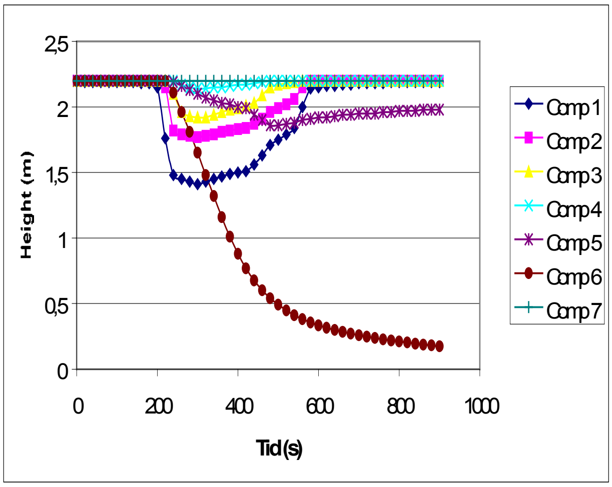
M/S Skåne, Cabin, Decaying HRR, Required ventilation in cabin

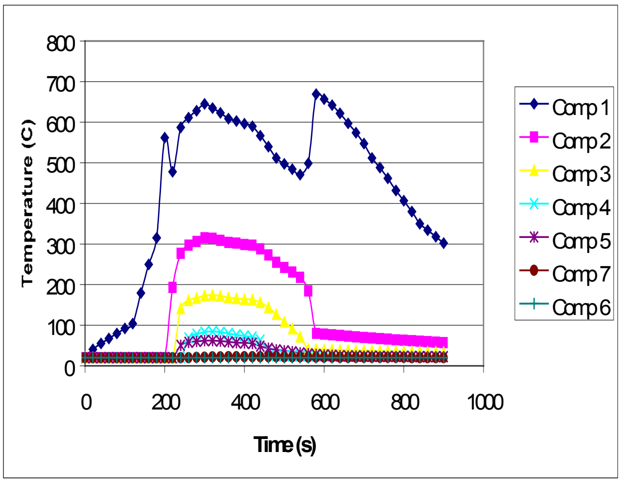




Scenario 1.6

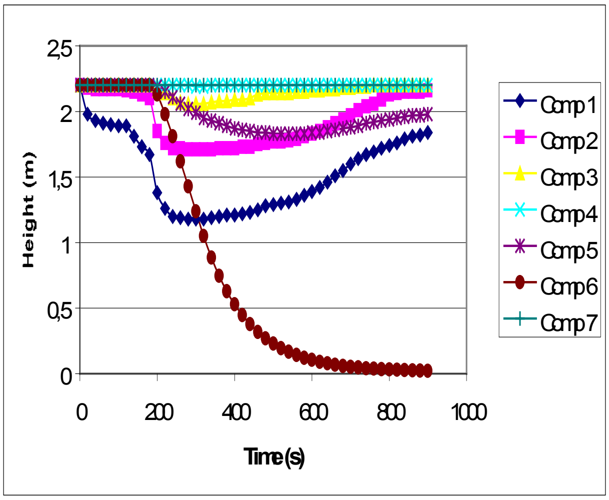
M/S Skåne, Cabin, Decaying HRR, Required ventilation in cabin and corridor

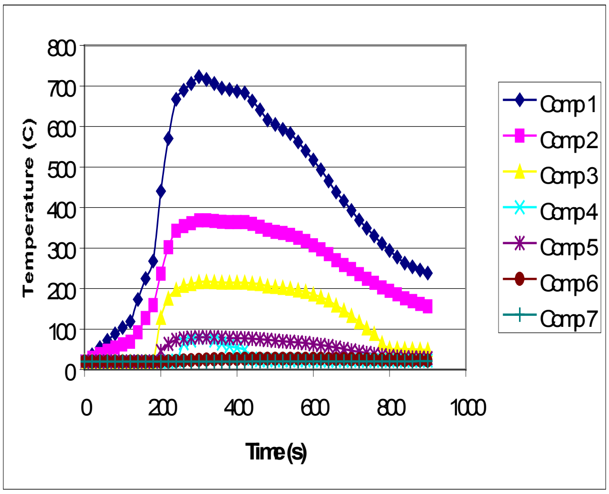




Scenario 1.7

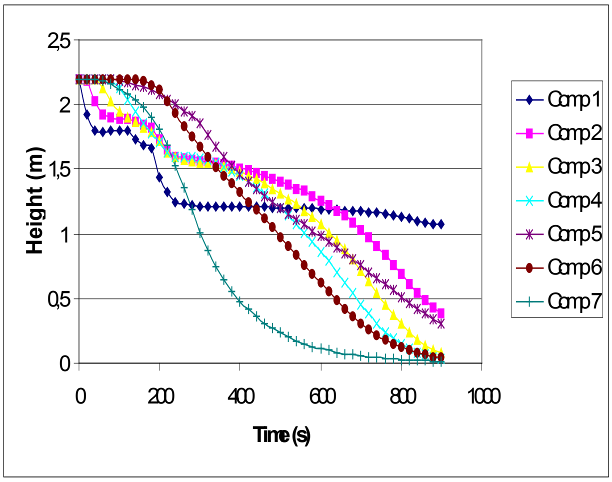
M/S Skåne, Cabin, Decaying HRR, Required ventilation in corridor

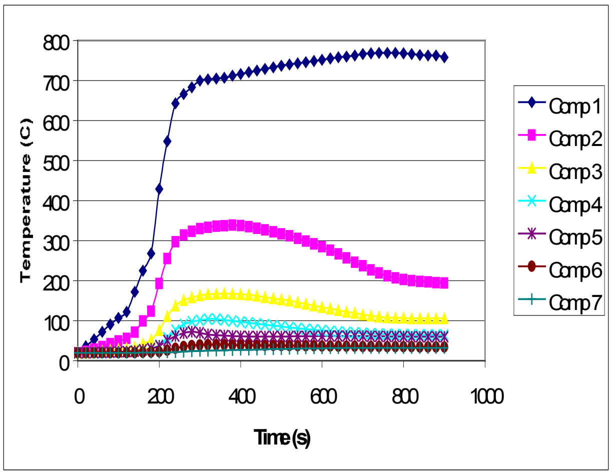




Scenario 1.8

M/S Skåne, Cabin, Constant HRR, No ventilation





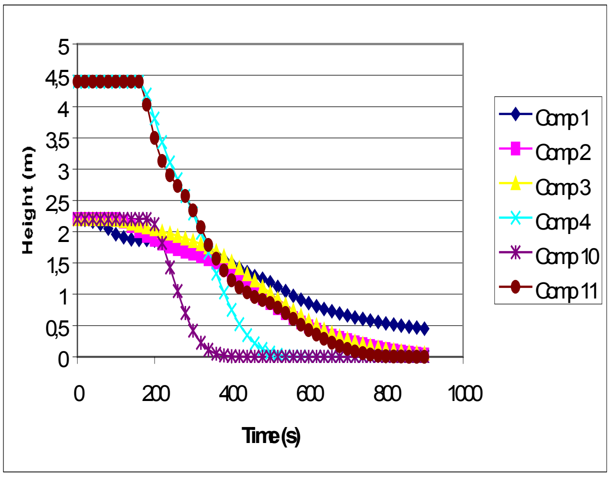
Appendix B

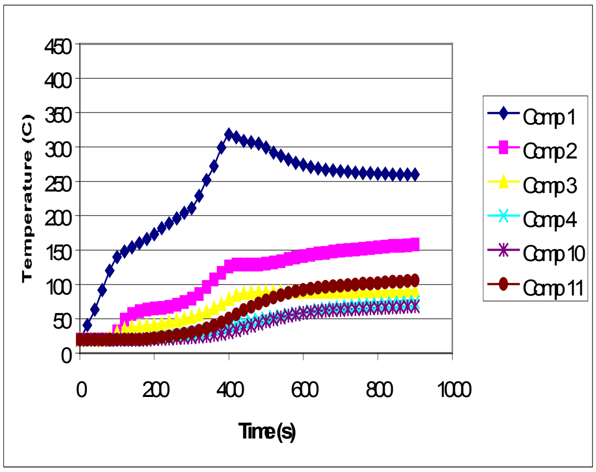
Computer simulations of Cafeteria

M/S Skåne

Scenario 2.1

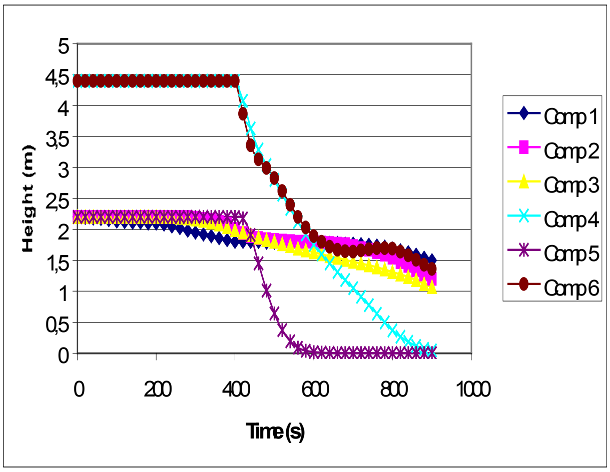
M/S Skåne, Cafeteria, Constant HRR, No ventilation

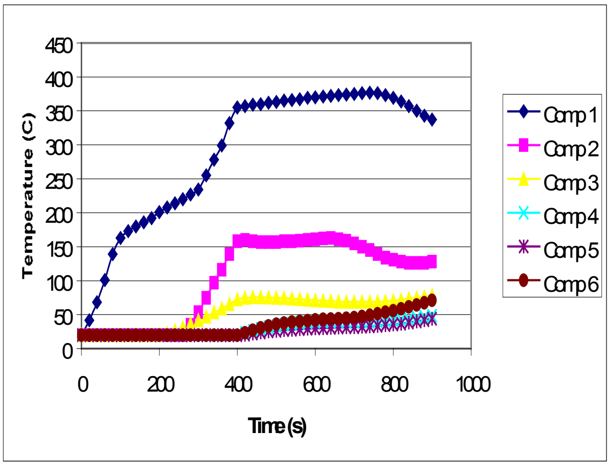




Scenario 2.2

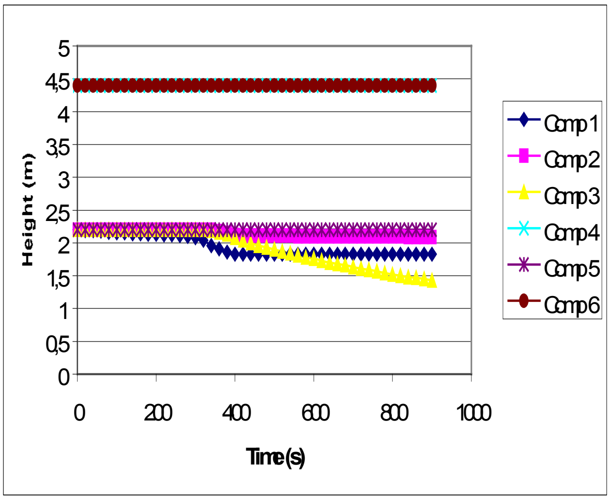
M/S Skåne, Cafeteria, Constant HRR, Existing ventilation in compartments 1 and 2.

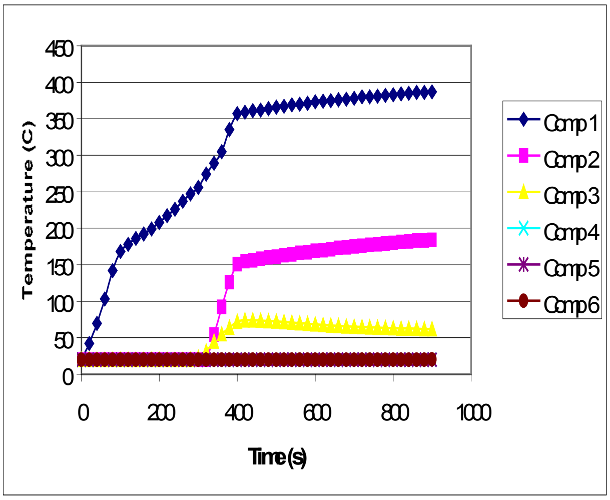




Scenario 2.3

M/S Skåne, Cafeteria, Constant HRR, Required ventilation in compartments 1 and 2.





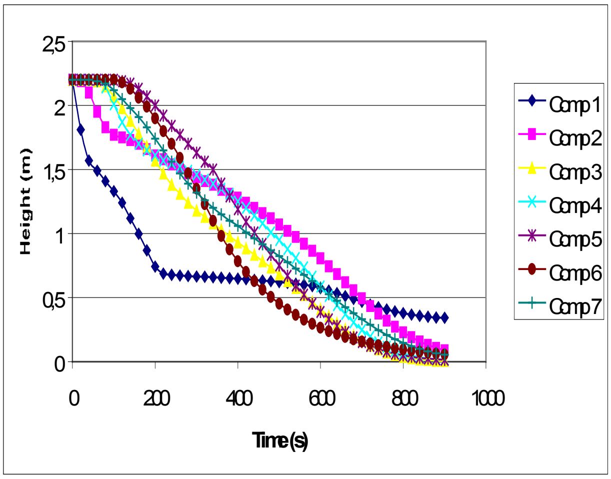
Appendix C

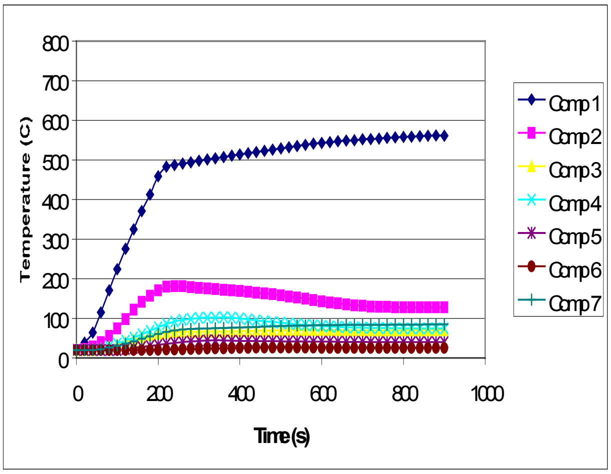
Computer simulations of Children's playroom

M/S Skåne

Scenario 3.1

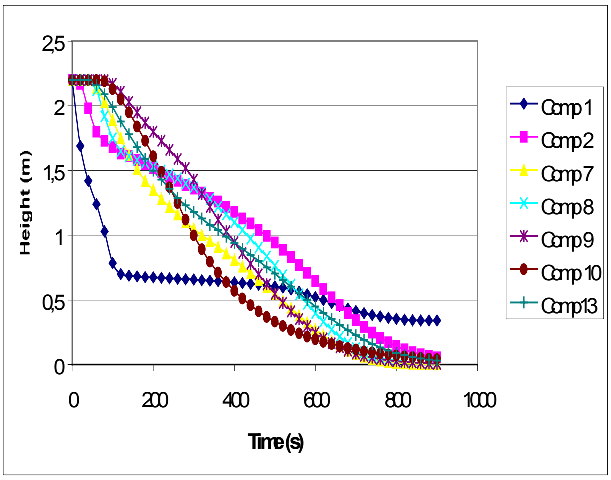
M/S Skåne, Children's playroom, 2MW Fast, No ventilation

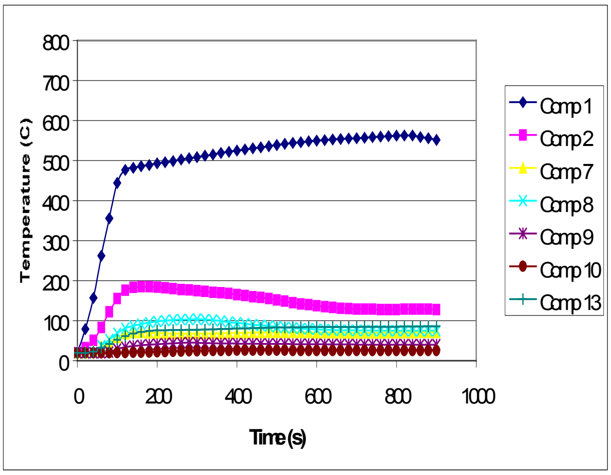




Scenario 3.2

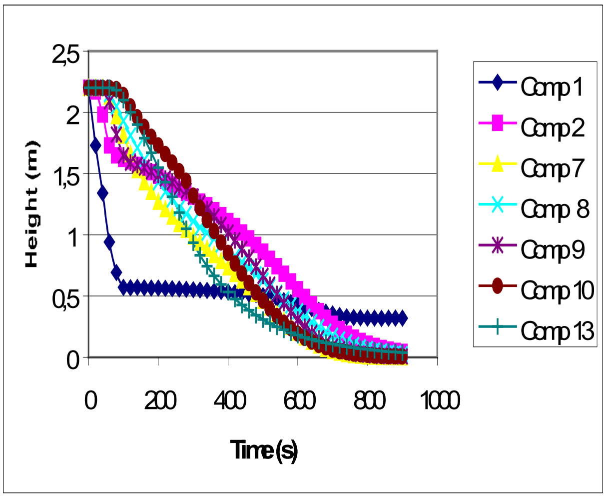
M/S Skåne, Children's playroom, 2MW Ultra Fast, No ventilation

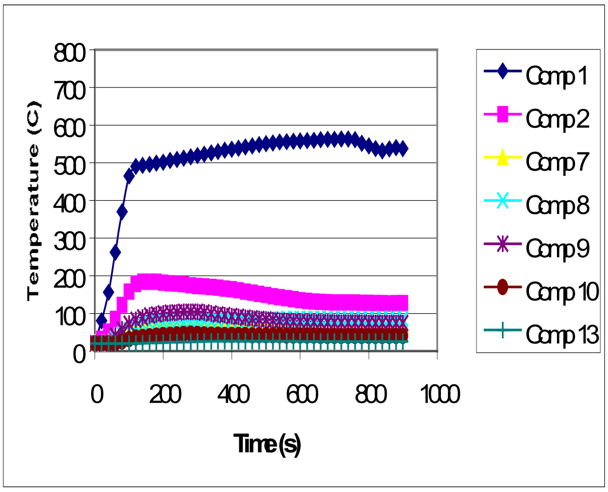




Scenario 3.3

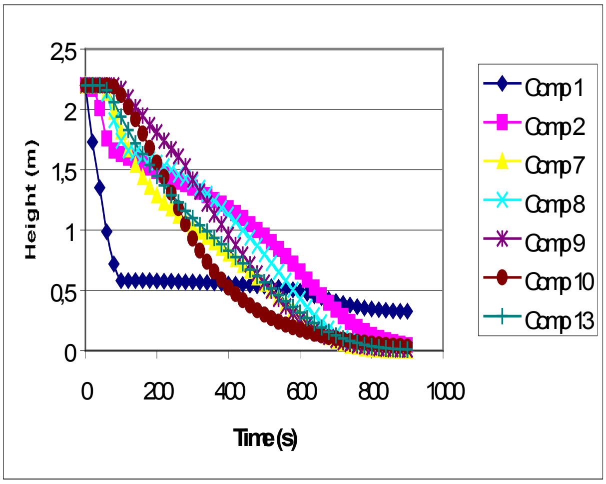
M/S Skåne, Children's playroom, 2MW Ultra Fast, Existing ventilation in compartment 1.

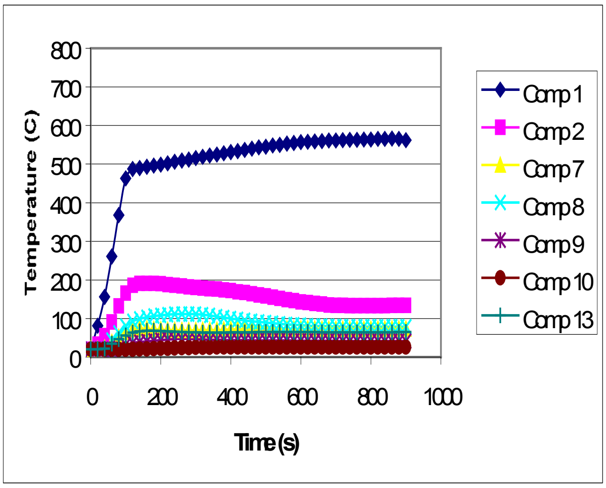




Scenario 3.4

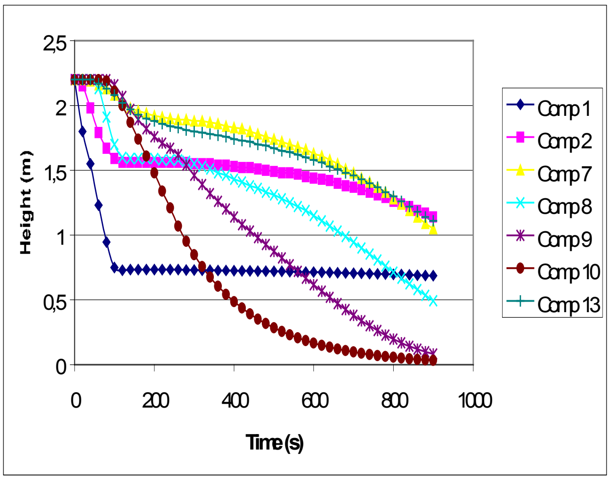
M/S Skåne, Children's playroom, 2MW Ultra Fast, Existing ventilation in compartments 1, 2 and 8.

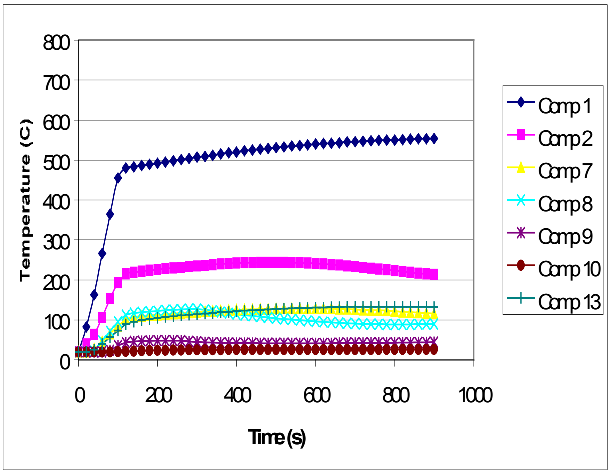




Scenario 3.5

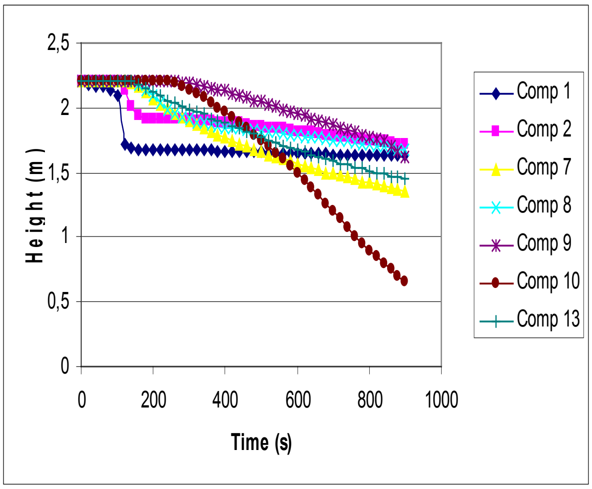
M/S Skåne, Children's playroom, 2MW Ultra Fast, Existing ventilation in compartments 1, 2, 7, 8 and 13.

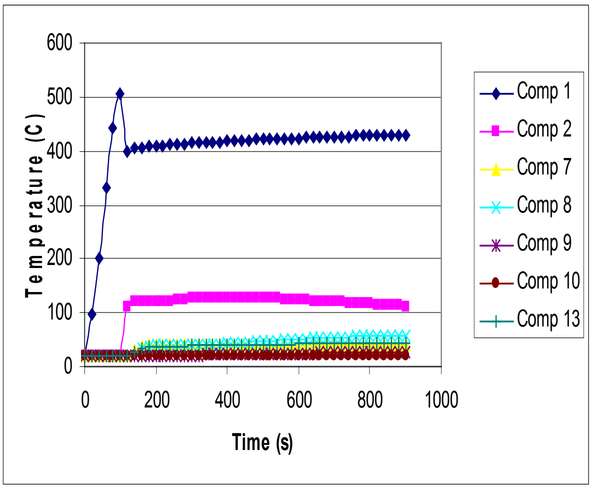




Scenario 3.6

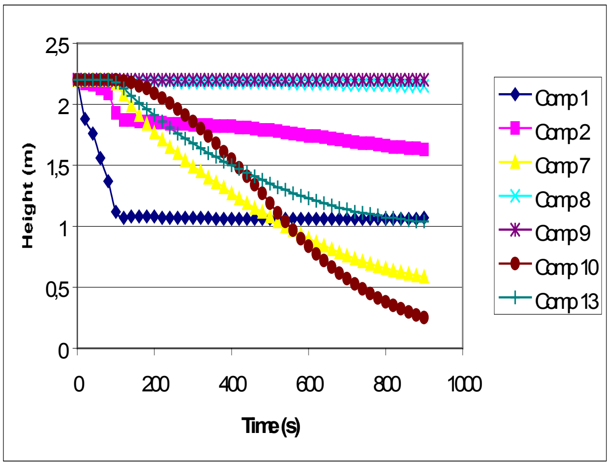
M/S Skåne, Children's playroom, 2MW Ultra Fast, Required ventilation in compartment 1.

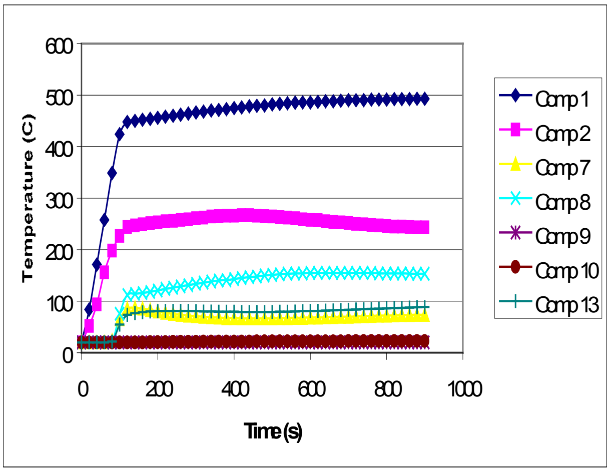




Scenario 3.7

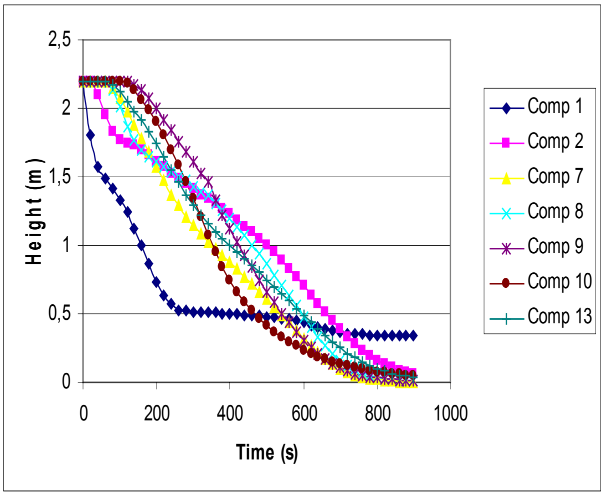
M/S Skåne, Children's playroom, 2MW Ultra Fast, Required ventilation in compartments 2 and 8.

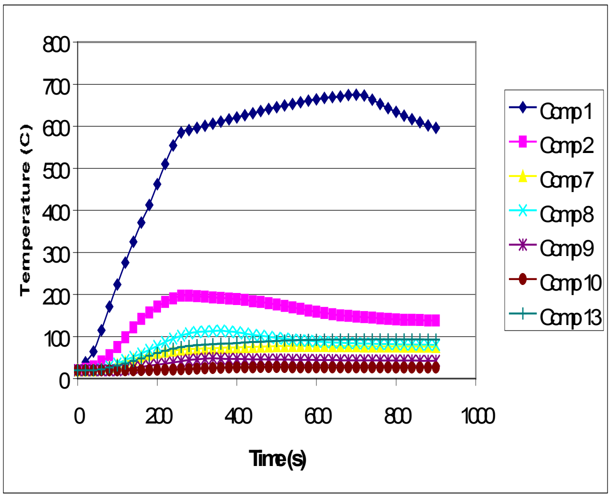




Scenario 3.8

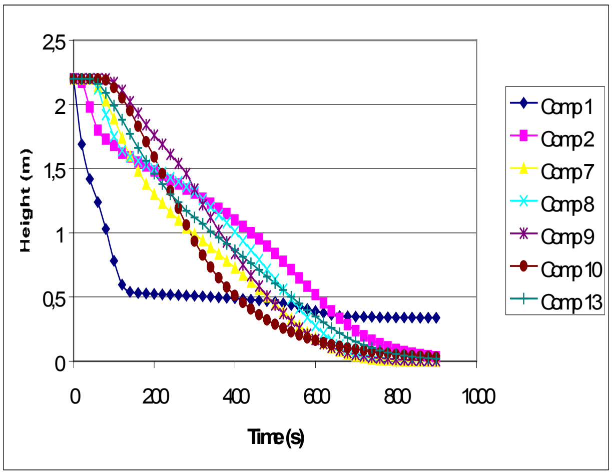
M/S Skåne, Children's playroom, 3MW Fast, No ventilation

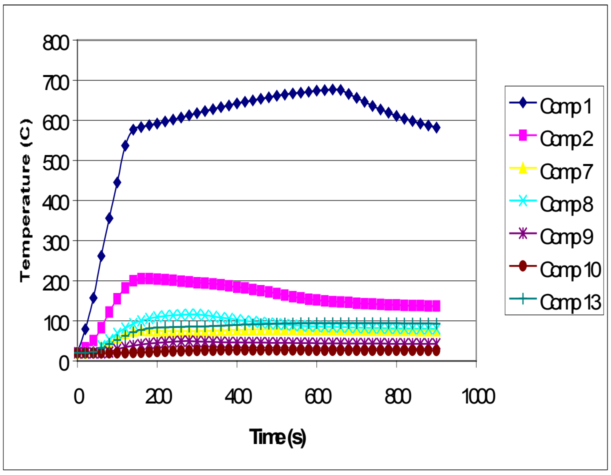




Scenario 3.9

M/S Skåne, Children's playroom, 3MW Ultra Fast, No ventilation





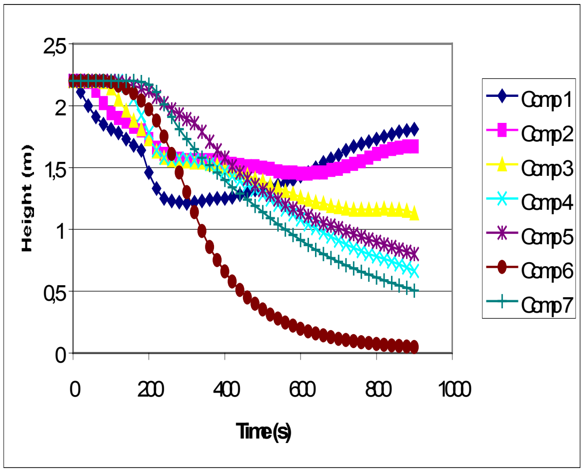
Appendix D

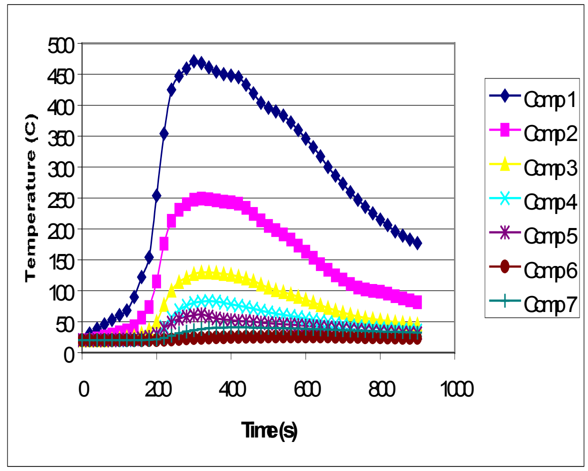
Computer simulations of Cabin

M/S Alternative

Scenario 4.1

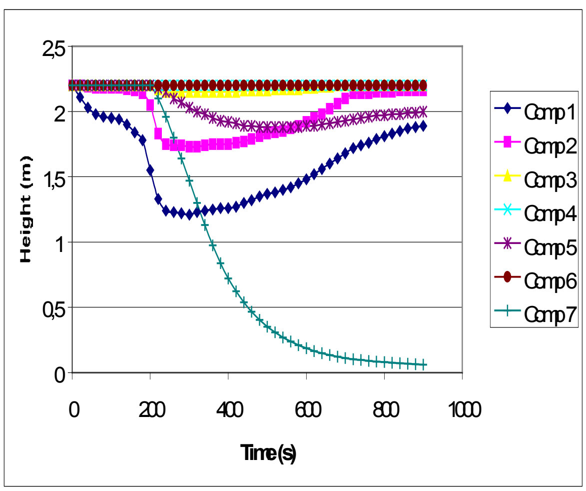
M/S Alternative, Cabin, HRR 1,64 MW, No ventilation

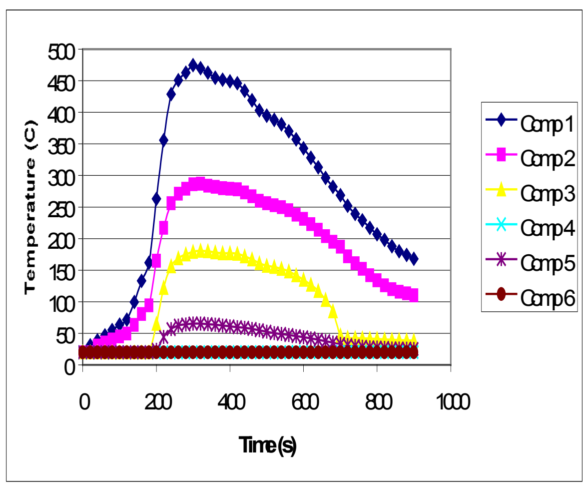




Scenario 4.2

M/S Alternative, Cabin, HRR 1,64 MW, Required ventilation in corridor





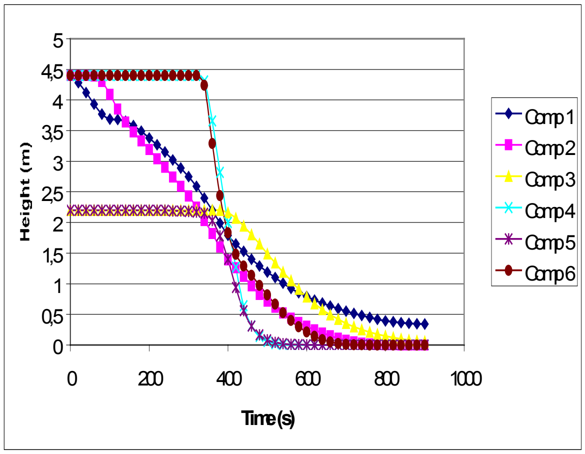
Appendix E

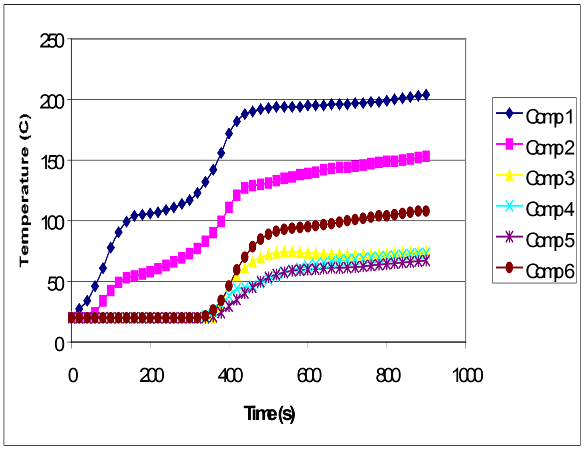
Computer simulations of Cafeteria

M/S Alternative

Scenario 5.1

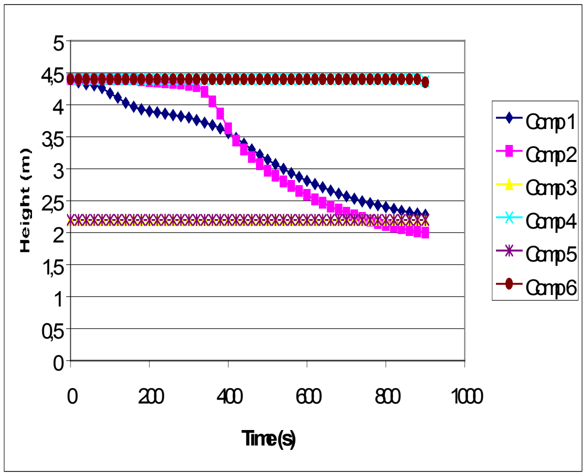
M/S Alternative, Cafeteria, HRR 3,24 MW, No ventilation

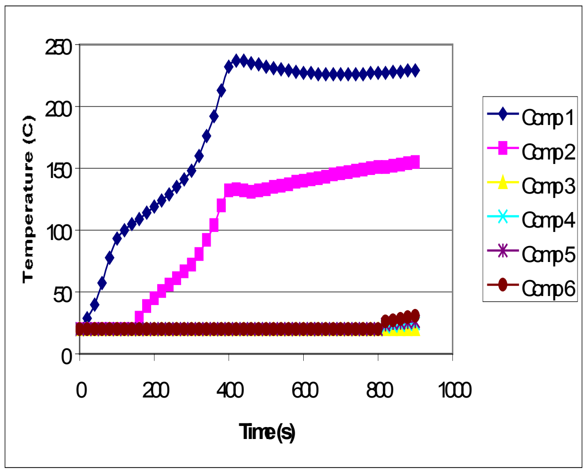




Scenario 5.2

M/S Alternative, Cafeteria, HRR 3,24 MW, Required ventilation in fire compartment





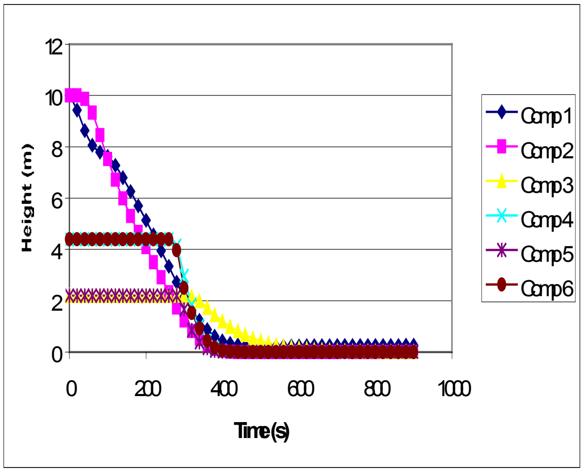
Appendix F

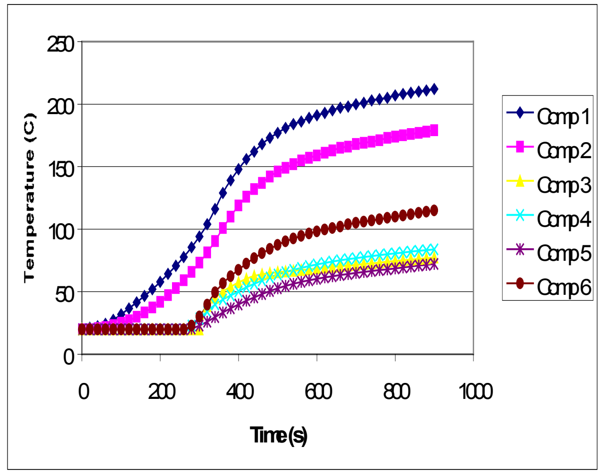
Computer simulations of Assembly Hall

M/S Alternative

Scenario 6.1

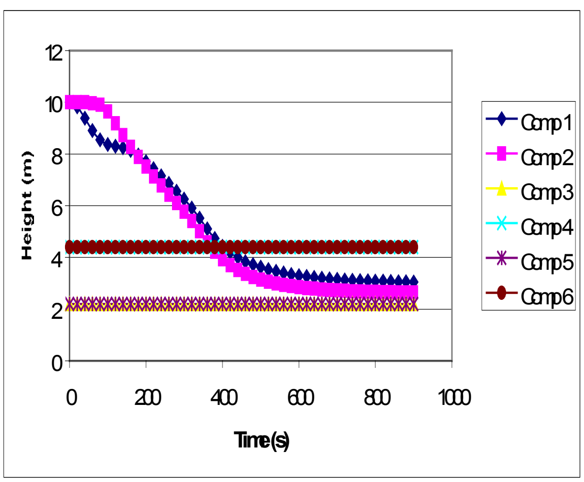
M/S Alternative, Assembly hall, HRR 6MW, No ventilation

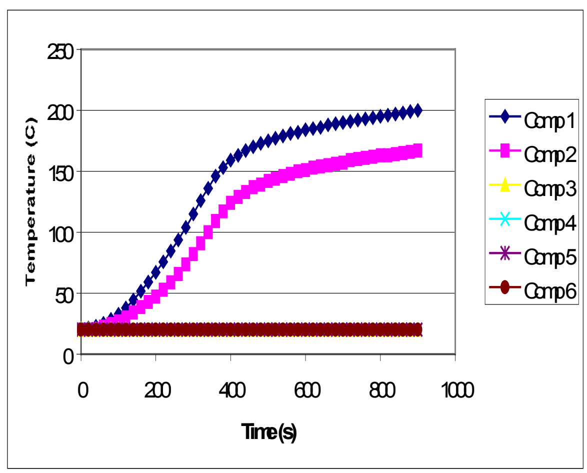




Scenario 6.2

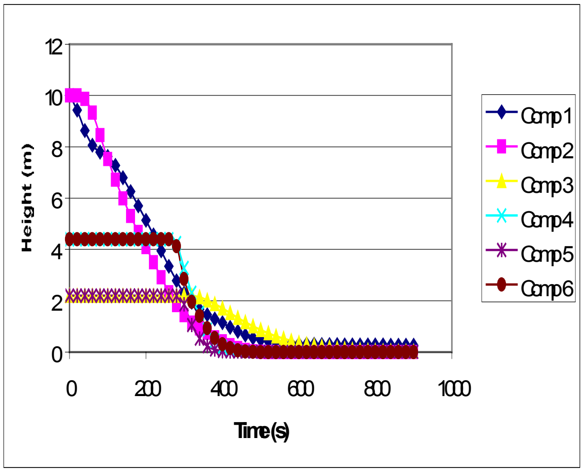
M/S Alternative, Assembly hall, HRR 6MW,
Required ventilation in fire comp. and comp. 2

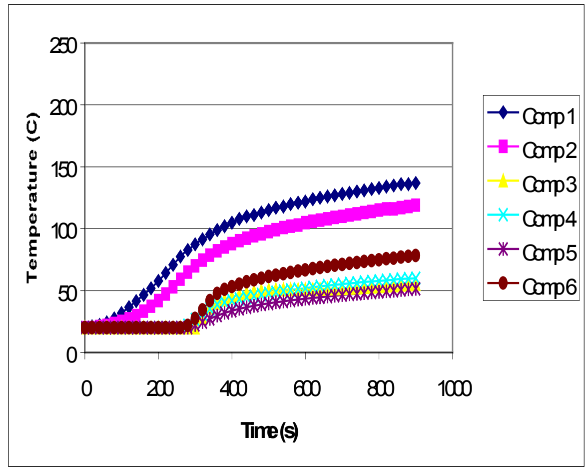




Scenario 6.3

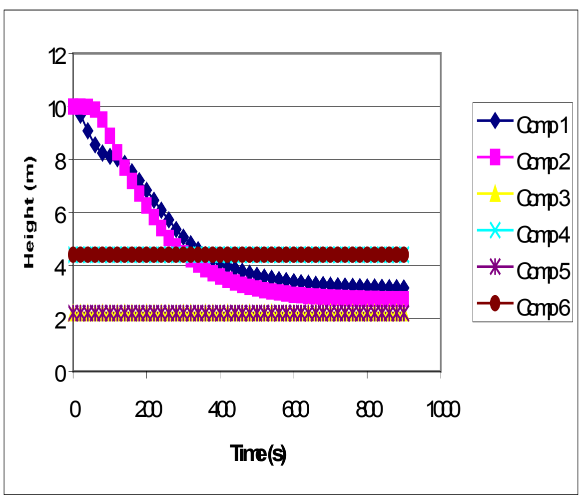
M/S Alternative, Assembly hall, HRR 3MW, No ventilation

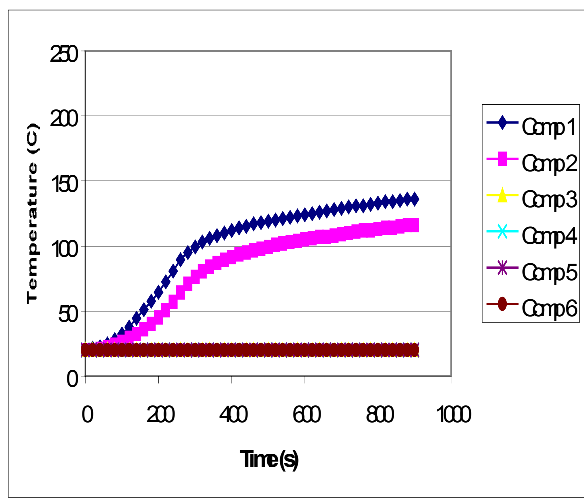




Scenario 6.4

M/S Alternative, Assembly hall, HRR 3MW,
Required ventilation in fire comp. and comp. 2





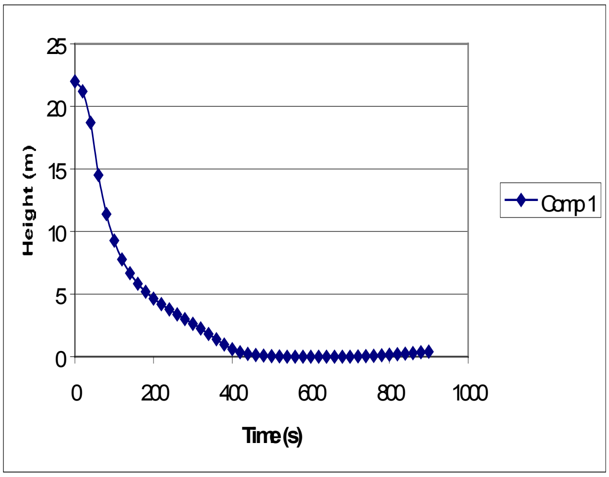
Appendix G

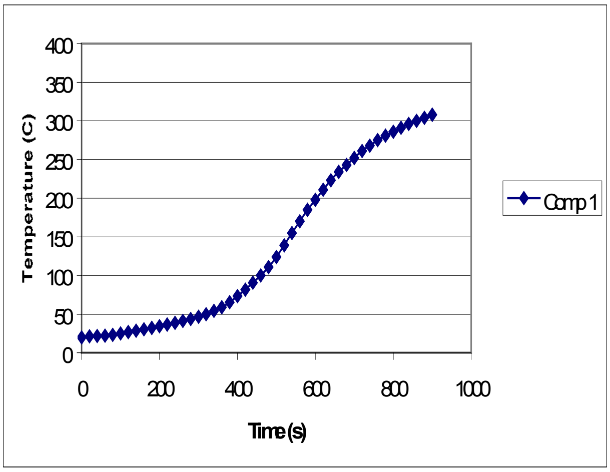
Computer simulations of Atrium

M/S Alternative

Scenario 7.1

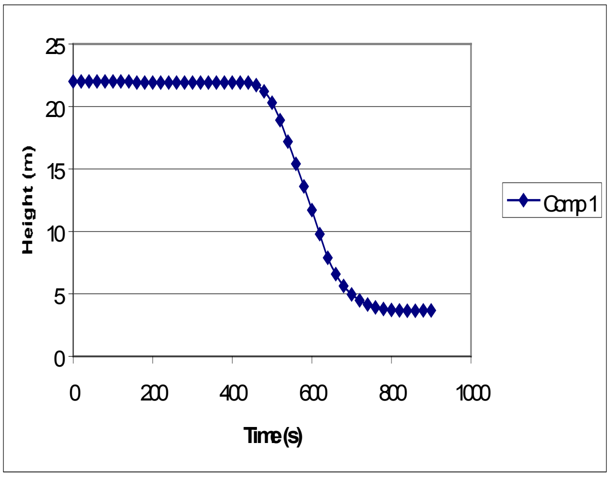
M/S Alternative, Atrium, HRR 6,4 MW, No ventilation

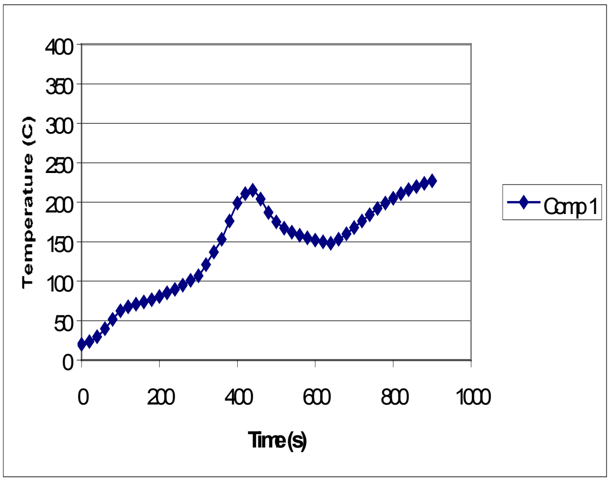




Scenario 7.2

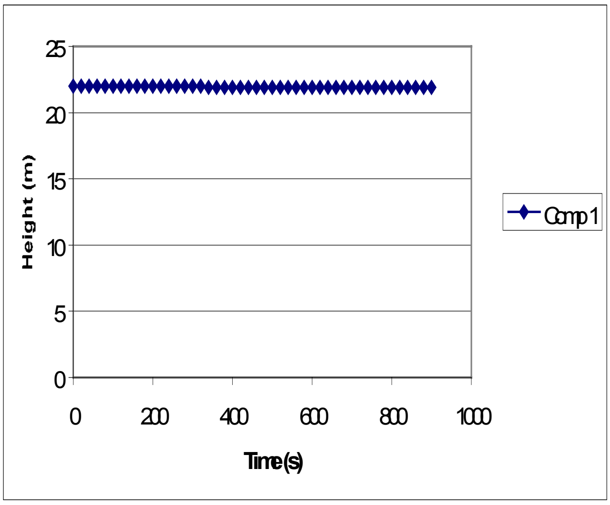
M/S Alternative, Atrium, HRR 6,4 MW, Required ventilation in atrium according to BBR

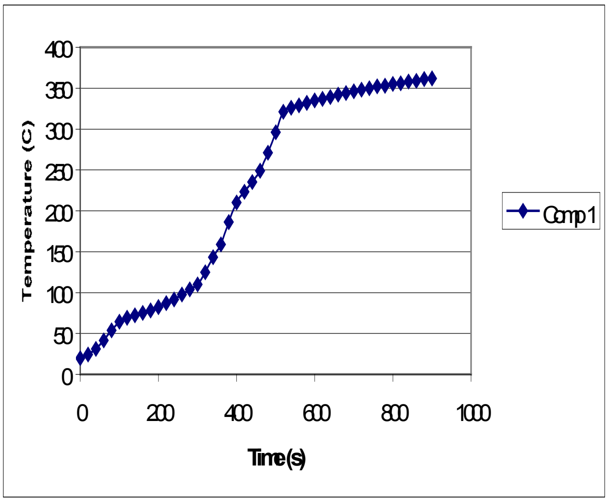




Scenario 7.3

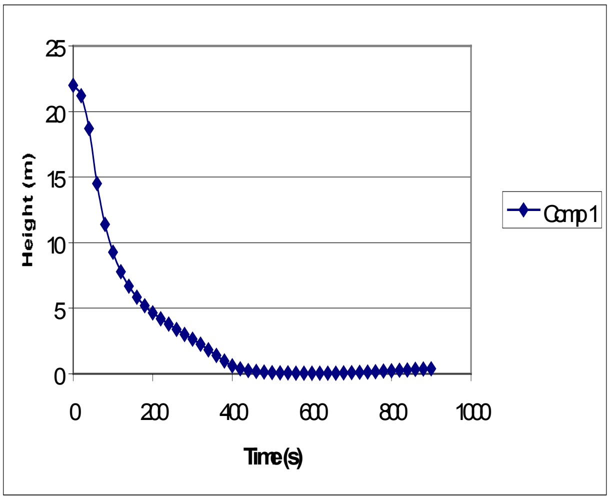
M/S Alternative, Atrium, HRR 6,4 MW,
Required ventilation in atrium according to SOLAS

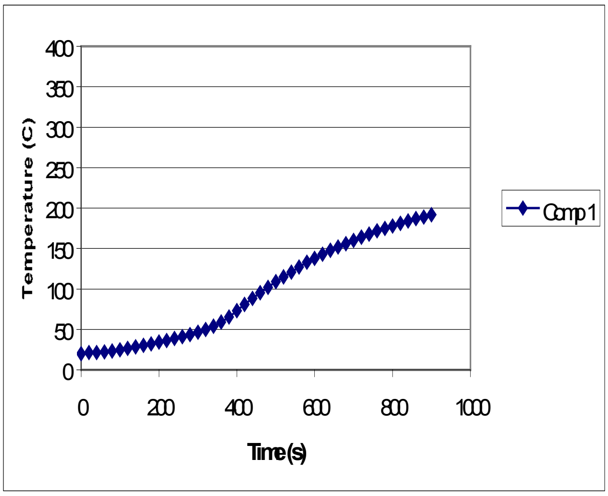




Scenario 7.4

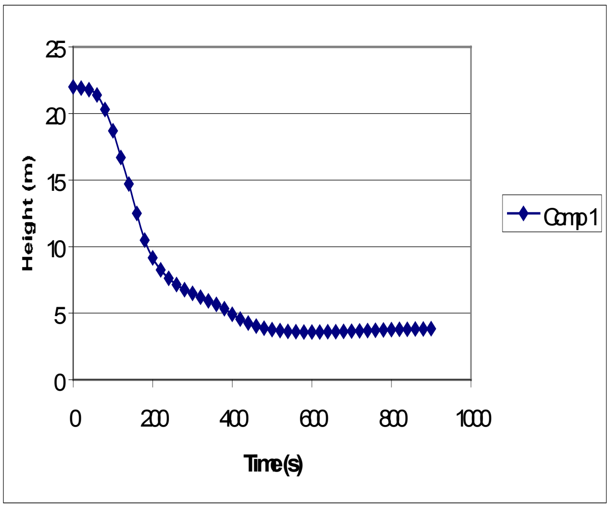
M/S Alternative, Atrium, HRR 3,2 MW, No ventilation

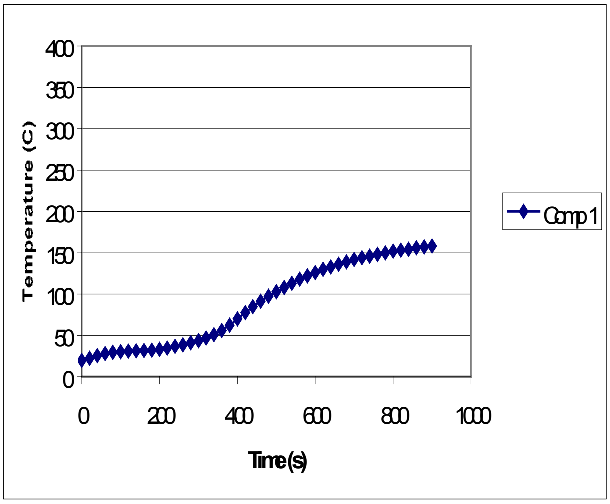




Scenario 7.5

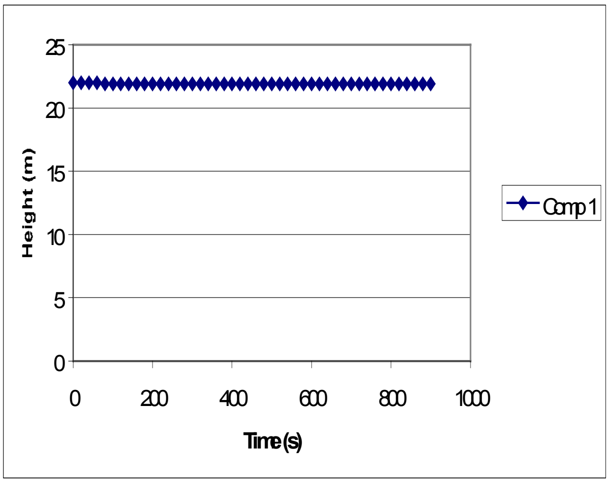
M/S Alternative, Atrium, HRR 3,2 MW,
Required ventilation in atrium according to BBR

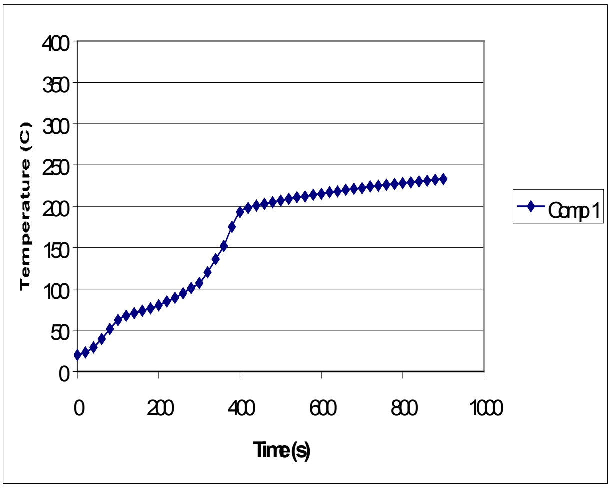




Scenario 7.6

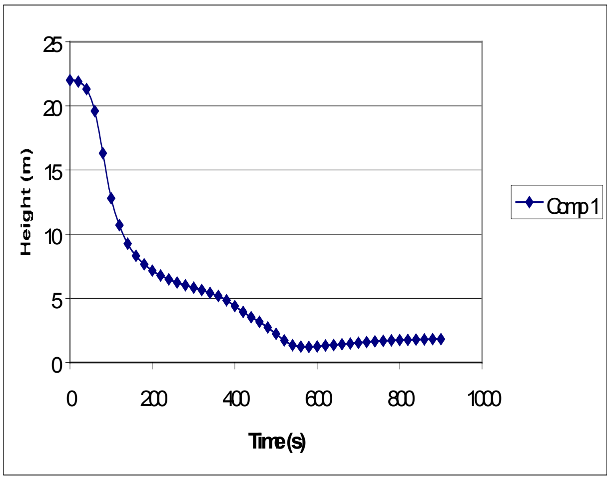
M/S Alternative, Atrium, HRR 3,2 MW,
Required ventilation in atrium according to SOLAS

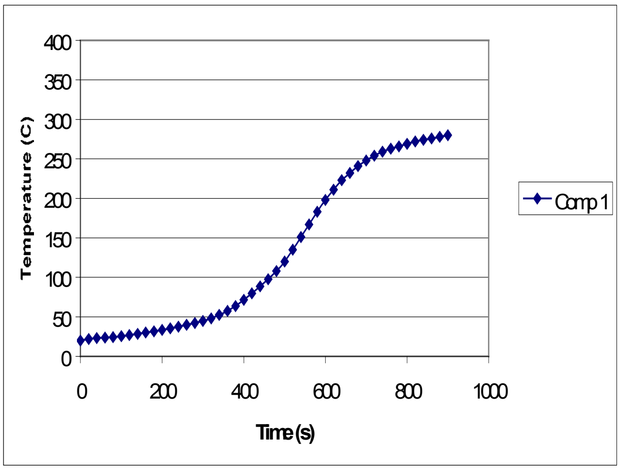




Scenario 7.7

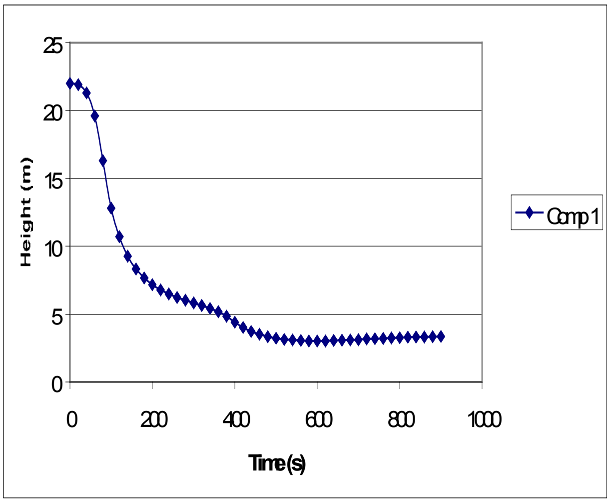
M/S Alternative, Atrium, HRR 6.4 MW,
Required ventilation in atrium according to SOLAS

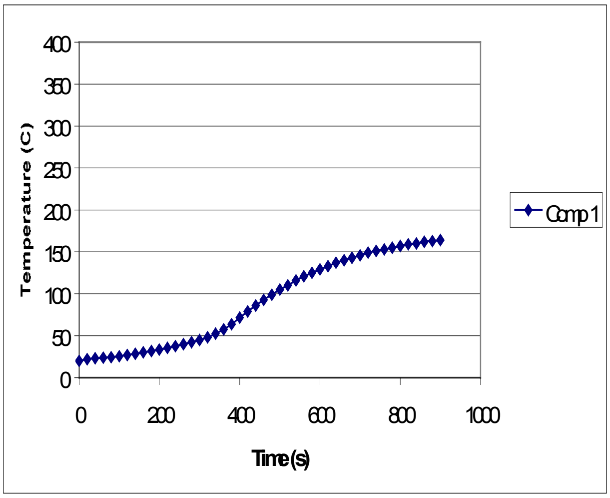




Scenario 7.8

M/S Alternative, Atrium, HRR 3.2 MW,
Required ventilation in atrium according to SOLAS





Appendix H

CFast

Description of CFAST

In engineering calculation questions as: How much does the simulated results differ from real ones? Which model gives the most accurate results? How can the model error be taken into account?, are of interest. At present there are three different types of deterministic fire models developed:

- "CFD-model" (Computational Fluid Dynamics), for example SOFIE,
- "Two-zone model", for example CFast and
- hand calculations.

Due to limited resources this report only considers two-zone models and hand calculations.

The computer program CFast uses two control volumes to describe a room, the upper volume contains hot combustion products and the lower contains fresh air. Each layer is characterised by one temperature, one gas concentration and one smoke density /22/. CFast contains a number of sub-models i.e. flame height, smoke velocity, the position of the interface, smoke temperature etc. These models are very complex and output from one sub-model becomes input to another. All sub-models contain approximations and assumptions. The total error of a prediction is a combination of all the assumptions made as input and the errors in sub-models.

According to comparison between full-scale experiments and CFast, the computer model seems to over predict the temperature and under predict the smoke layer height. The over prediction seems to increase with an increasing temperature. The error CFast corresponds to is an over prediction of the temperature by 25-40% and an under prediction of the measured interface by 10-40% /22/. The uncertainty in simulations with CFast varies over the time. This report only considers the conditions at the end of the simulation time where the percent figures mentioned above are valid. Uncertainties for other time periods earlier during the simulation have to be considered separately.

Engineers modelling the same situation with the same simulation tool will come up with predictions that are not exactly the same. This is inevitable to avoid. The assumptions made may not be the ultimate ones /17/.

Appendix I

Hand calculations

Design fire for Scenario 1

Maximum heat release rate:

A compartment fire can be either fuel controlled or ventilation controlled. A fuel controlled fire has an excess of oxygen and not sufficient fuel, while a ventilation controlled fire has an exsecc of fuel and the limiting factor is oxygen. The post-flash over fire will be ventilation-limited, meaning that the maximum HRR depends on the amount of air supplied to the fire, defined by the so called ventilation factor $A\sqrt{H}$. The maximum mass flow rate of air can be estimated on basis of the opening dimensions of the compartment. / referera till Björns bok/

$\dot{m}_a = 0.5 \times A_0 \times \sqrt{H_0}$ where

$\dot{m}_a$ = mass flow rate (kg/s)
A_0 = opening area (m^2)
H_0 = opening height (m)

Each kg of oxygen involved in fire produces around 13.2 MJ. 23% of the air entering the compartment is oxygen, why the maximum heat release rate becomes:

$$\left.\begin{array}{l} \dot{Q}_{\max} = 1.518 \times A_0 \times \sqrt{H_0} \\ A_0 = 0.65 \times 2.1 m^2 \\ H_0 = 2.1 m \end{array}\right\} \Rightarrow \dot{Q}_{\max} = 3.00 MW$$

The combustion efficiency, χ, is assumed to be 0.7.

$$\Rightarrow \dot{Q}_{eff} = 0.7 \times 3.00 MW = 2.1 MW$$

Input for design fire:

The maximum heat release rate, developed during full-scale experiments is 1.64MW (Y0/10), /refera till särdquist/. The different HRR:s for Scenarios 1.1 to1.8 are presented in Table I- 1 and Table I- 2.

Table I- 1: Heat release rate with a decay phase, based on full-scale experimental data /Referara till Särdquist/

Scenario 1.1-1.7	
time **(s)**	$\dot{Q}$ **(kW)**
0	0
30	10
60	20
90	30
120	40
180	190
240	1430
300	1640
360	1400
420	1280
480	930
540	790
600	560
660	340
720	200
780	130
840	80
900	60

Table I- 2: Heat release rate with a continuing constant HRR after the growth phase, based on maximum HRR in full-scale experimental data (Y0/10), /Referara till Särdquist/

Scenario 1.8	
time **(s)**	$\dot{Q}$ **(kW)**
0	0
30	10
60	20
90	30
120	40
180	190
240	1430
300	1640
360	1640
420	1640
480	1640
540	1640
600	1640
660	1640
720	1640
780	1640
840	1640
900	1640

Design fire for Scenario 2

Input for design fire:

The fire originates in a television set with a certain HRR, $\dot{Q}_{\mathbf{TV}}$, and spreads to nearby wooden structures, $\dot{Q}_{\mathbf{Particle\ Board}}$, after 90 seconds. $\dot{Q}_{\mathbf{Total}}$ is the total amount of $\dot{Q}_{\mathbf{TV}}$ and $\dot{Q}_{\mathbf{Particle\ Board}}$, which both are based on full scale experimental data (Y1/22, O4/22) /Referera till Särdquist/. The different HRR:s are presented in Table I- 3.

Table I- 3: Heat release rates for the different components of the cafeteria fire and the combination of these.

Scenario 2.1-2.3			
time **(s)**	$\dot{Q}_{\mathbf{TV}}$ **(kW)**	$\dot{Q}_{\mathbf{Particle\ Board}}$ **(kW)**	$\dot{Q}_{\mathbf{Total}} = \dot{Q}_{\mathbf{TV}} + \dot{Q}_{\mathbf{PB}}$ **(kW)**
0	0	-	0
30	60	-	60
60	250	-	250
90	530	0	530
120	560	70	630
180	560	190	750
240	560	400	960
300	560	700	1260
360	560	1680	2240
390	560	2680	3240
600	560	2680	3240

Design fire for Scenario 3

Heat release rate from a pool fire:

The HRR was approximated as a polymer pool fire. The exact polymer that the plastic balls are made up of is not known, but is approximated with the fire specific properties of PVC. /referara till Björns bok/ . The pool area was measured on site and was approximately 9.0m^2.

$$\dot{Q} = A_f \times \dot{m}'' \times \Delta H_c \times \chi$$

A_f = fuel area (m^2)
$\dot{m}''$ = mass burning rate per unit area (kg/ m^{2}s)
ΔH_c = heat of combustion (MJ/ kg)
χ = combustion efficiency

$\Rightarrow$

$$\left.\begin{array}{l} \dot{m}'' = 0.016 kg/m^2 s \\ \Delta H_c = 16.4 MJ/kg \\ \chi = 0.7 \\ A_f = 9.0 m^2 \end{array}\right\} \Rightarrow \dot{Q} = 1.65 MW$$

Maximum heat release rate:

The post-flash over fire will be ventilation-limited, meaning that the maximum HRR depends on the amount of air supplied to the fire. The maximum mass flow rate of air can be estimated on basis of the opening dimensions of the compartment. / referera till Björns bok/

$$\dot{m}_a = 0.5 \times A_0 \times \sqrt{H_0}$$ where

$\dot{m}_a$ = mass flow rate (kg/s)
A_0 = opening area (m^2)
H_0 = opening height (m)

Each kg of oxygen involved in fire produces around 13.2 MJ. 23% of the air entering the compartment is oxygen, why the maximum heat release rate becomes:

$$\left.\begin{array}{l} \dot{Q}_{max} = 1.518 \times A_0 \times \sqrt{H_0} \\ A_0 = 0.9 \times 2.1 m^2 \\ H_0 = 2.1 m \end{array}\right\} \Rightarrow \dot{Q}_{max} = 4.16 MW$$

The combustion efficiency, χ, is assumed to be 0.7.

$$\Rightarrow \dot{Q}_{eff} = 0.7 \times 4.16 MW = 2.91 MW$$

Input for design fires:
The chosen maximum heat release rates were 2.0MW and 3.0MW with growth rates corresponding to NFPA's Fast and Ultra Fast.

The design fires were assumed to follow the development of $\dot{Q} = \alpha t^2$ where $\alpha_{Fast} = 0.047$ kW/s^2 and $\alpha_{Ultra\ Fast} = 0.19$ kW/s^2. The different HRR:s for Scenarios 3.1 to 3.9 are presented in Table I- 4 to Table I- 7 below.

Table I- 4: HRR for 2.0MW fire, Fast development.

Scenario 3.1	
time **(s)**	$\dot{Q}$ **(kW)**
0	0
30	42.3
60	169
90	381
120	677
180	1523
206	2000
300	2000
600	2000
900	2000

Table I- 5: HRR for 3.0MW fire, Fast development.

Scenario 3.8	
time **(s)**	$\dot{Q}$ **(kW)**
0	0
30	42.3
60	169
90	381
120	677
180	1523
253	3000
300	3000
600	3000
900	3000

Table I- 6: HRR for 2.0MW fire, Ultra Fast development.

Scenario 3.2-3.7	
time **(s)**	$\dot{Q}$ **(kW)**
0	0
30	171
60	684
90	1539
102	2000
300	2000
600	2000
900	2000

Table I- 7: HRR for 3.0MW fire, Ultra Fast development.

Scenario 3.9	
time **(s)**	$\dot{Q}$ **(kW)**
0	0
30	171
60	684
90	1539
120	2736
126	3000
300	3000
600	3000
900	3000

Design fire for Scenario 6

Input for design fires:

The chosen maximum heat release rates were 3.0MW and 6.0MW with a growth rate corresponding to NFPA's Fast.

The design fires were assumed to follow the development of $\dot{Q} = \alpha t^2$ where $\alpha_{Fast} = 0.047$ kW/s^2. The different HRR:s for Scenarios 6.1 to 6.4 are presented in Table I- 8 and Table I- 9 below.

Table I- 8: HRR for 6.0MW fire, Fast development.

Scenario 6.1-6.2	
time **(s)**	$\dot{Q}$ **(kW)**
0	0
30	42.3
60	169
90	381
120	677
180	1523
253	3000
291	4000
326	5000
357	6000
900	6000

Table I- 9: HRR for 3.0MW fire, Fast development.

Scenario 6.3-6.4	
time **(s)**	$\dot{Q}$ **(kW)**
0	0
30	42.3
60	169
90	381
120	677
180	1523
253	3000
300	3000
600	3000
900	3000

Design fire for Scenario 7

Input for design fires:
Scenarios 7.4, 7.5, 7.6 and 7.8:
The design fire is identical to the one in Scenario 2. The fire originates in a television set with a certain HRR, $\dot{Q}_{\mathbf{TV}}$, and spreads to nearby wooden structures, $\dot{Q}_{\mathbf{Particle\ Board}}$, after 90 seconds. The total HRR of the design fire, $\dot{Q}_{\mathbf{Total}}$, is the total amount of $\dot{Q}_{\mathbf{TV}}$ and $\dot{Q}_{\mathbf{Particle\ Board}}$, which both are based on full scale experimental data (Y1/22, O4/22) /Referera till Särdquist/. The different HRR:s are presented in Table I- 10.

Table I- 10: Heat release rates for the different components of the3.2MW atrium fire and the combination of these.

Scenario *7.4, 7.5, 7.6 and 7.8*			
time **(s)**	$\dot{Q}_{\mathbf{TV}}$ **(kW)**	$\dot{Q}_{\mathbf{Particle\ Board}}$ **(kW)**	$\dot{Q}_{\mathbf{Total}} = \dot{Q}_{\mathbf{TV}} + \dot{Q}_{\mathbf{PB}}$ **(kW)**
0	0	-	0
30	60	-	60
60	250	-	250
90	530	0	530
120	560	70	630
180	560	190	750
240	560	400	960
300	560	700	1260
360	560	1680	2240
390	560	2680	3240
600	560	2680	3240

Scenarios 7.1, 7.2, 7.3 and 7.7:

The design fire is identical to the one in scenario 7.4, 7.5, 7.6 and 7.8 for the first 390 seconds. The fire originates in a television set with a certain HRR, $\dot{Q}_{\mathbf{TV}}$, and spreads to nearby wooden structures, $\dot{Q}_{\mathbf{Particle\ Board}}$, after 90 second. These are based on full-scale experimental data (Y1/22, O4/22) /Referera till Särdquists/. After 390 seconds the fire is assumed to spread to additional interior. This interior was set to have the characteristics of a material with an Ultra Fast growth rate (NFPA). The total HRR of the design fire, $\dot{Q}_{\mathbf{Total}}$, is the sum of $\dot{Q}_{\mathbf{TV}}$, $\dot{Q}_{\mathbf{Particle\ Board}}$ and $\dot{Q}_{\mathbf{Ultra\ Fast}}$. The different HRR:s are presented in Table I-11.

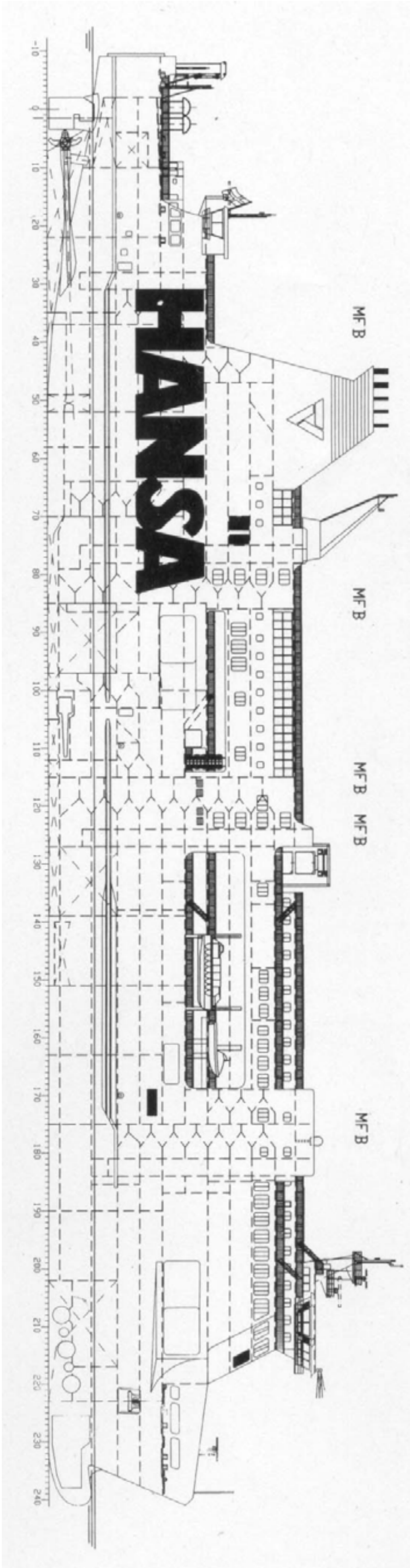
Table I- 11: Heat release rates for the different components of the 6.4 MW atrium fire and the combination of these.

Scenario 7.1-7.3 and 7.7				
time **(s)**	$\dot{Q}_{\mathbf{TV}}$ **(kW)**	$\dot{Q}_{\mathbf{Particle\ Board}}$ **(kW)**	$\dot{Q}_{\mathbf{Ultra\ Fast}}$ **(kW)**	$\dot{Q}_{\mathbf{Total}} = \dot{Q}_{\mathbf{TV}} + \dot{Q}_{\mathbf{PB}} + \dot{Q}_{\mathbf{Ultra\ Fast}}$ **(kW)**
0	0	-	-	0
30	60	-	-	60
60	250	-	-	250
90	530	0	-	530
120	560	70	-	630
180	560	190	-	750
240	560	400	-	960
300	560	700	-	1260
360	560	1680	-	2240
390	560	2680	0	3240
453	560	2680	760	4000
486	560	2680	1760	5000
518	560	2680	3160	6400

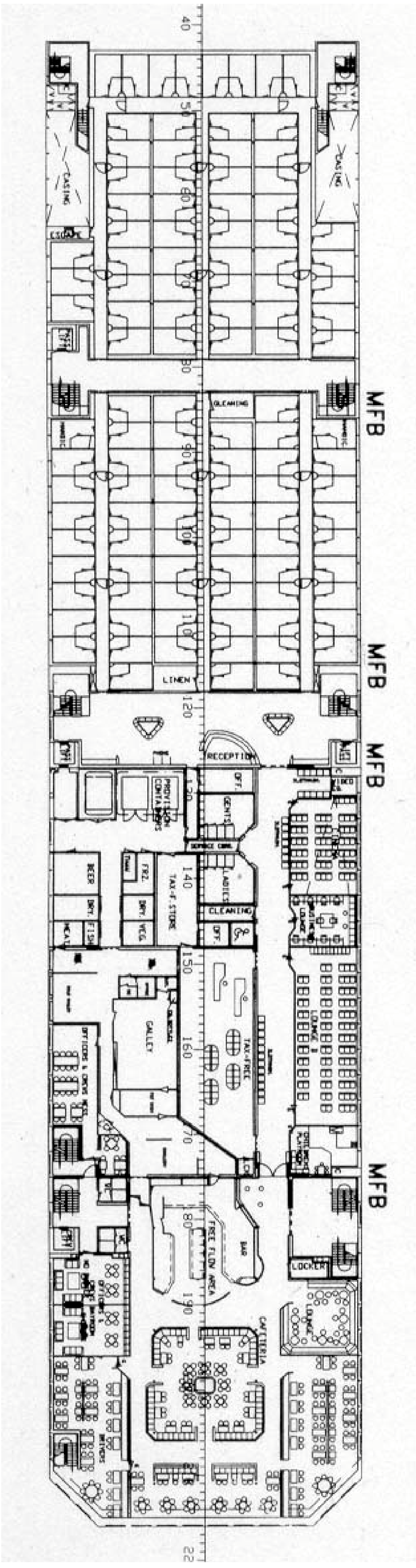
Appendix J

Drawings

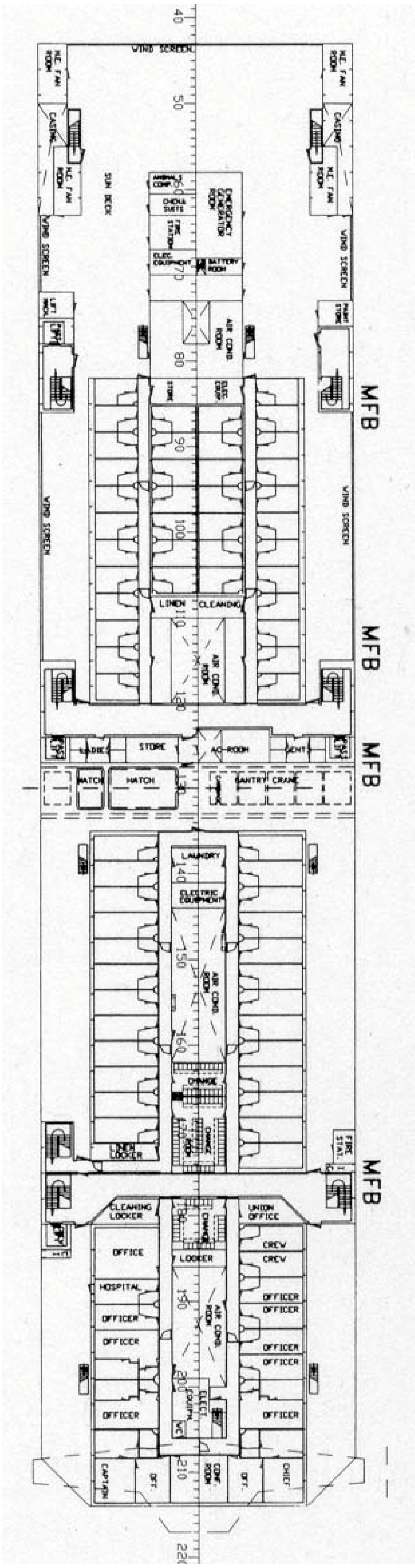
Section



Deck 9



Deck 10



Appendix K

Regression analysis

A regression equation was derived to analyse how the smoke layer height, H_s, depends on different heat release rates, $\dot{Q}$ and ventilation capacities, $\dot{V}$. The uncertainties of the equation were then supposed to be analysed using statistical data and the Monte Carlo analysis method. The analysis was set to be valid for the geometries in an assembly hall with the dimensions $31 \times 19 \times 10$ m^3. The heat release rate $\dot{Q}$ was set to vary between 1.5 MW and 6 MW and the extraction capacity $\dot{V}$ was set to vary between 6 m^3/s and 20 m^3/s. These figures are based on the design fires set and the results given from the quantitative risk analysis for *M/S Skåne* and *M/S Alternative.* The model is only valid within these intervals. The theory behind a derivation of a regression equation is described in /21/. The derivation of the regression equation in this report was carried out in the computer software Microsoft Excel.

The best fit equation derived in Microsoft Excel became:

$$H_{smokelayer} = 100 \times \dot{Q}^{-0.865} \times \dot{V}^{1..356}$$, where $R^2 = 0.935$.

The closer R^2 gets to 1.0, the better the correspondence is between the calculation model and the parameters analysed. The correspondence can be said to be good and the expression could be used for its purpose if proper statistical data on typical heat release rates was available. The result of fitting is shown in the figure below.

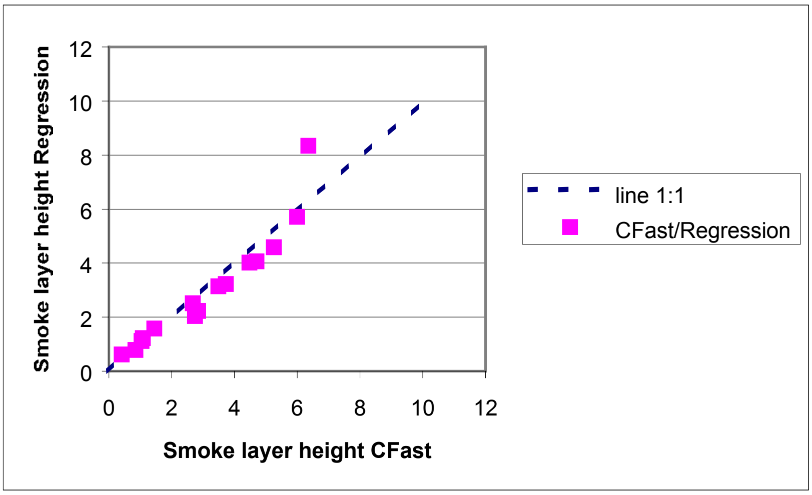


Figure 73: Result of regression analysis of smoke layer height.