Large-scale fire tests in a passenger cabin

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Abstract

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A number of large-scale fire experiments have been made in passenger cabins to evaluate the performance of a composite superstructure on a Ro-Pax vessel. Two cabins and a corridor were constructed within a section of fire insulated PVC + GFRP composite decks and bulkhead. The construction and cabins were made of realistic material and furnishing. A series of experiments were made to investigate effect of ventilation, fire detection and sprinkler systems, also for fires on the outside of the composite bulkhead. Effects of simulated fault functions in safety systems were tested and in a final test a cabin flashover fire burned for more than 30 minutes. The results show that the composite structure can withstand more than 60 minutes of uncontrolled cabin fire without critical damage, and that an outside drencher system is efficient in preventing window fires from propagating. It also shows that normal approved cabin interiors can produce a very severe fire in short time if all safety systems malfunction.

Key words: Large-scale fire tests, ships, passenger cabin, water mist systems

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The project was financed by VINNOVA (Swedish Governmental Agency for Innovation Systems), project number 27020-1 in co-operation with STENA Rederi AB.

The following companies further sponsored the project with working hours, material and equipment:

- Brødrene Aa AS
- Callenberg Fläkt Marine AB
- Consilium Fire & Gas AB
- DIAB AB
- Isolamin AB
- Kockums AB
- FiReCo AS
- Ultra Fog AB
- Hellbergs International AB
- ScanMarine AB
- Thermal Ceramics Europe
- TYCO Building Services Products (Sweden)

Involved in the project was also a DNV-led subgroup of the EU project SAFEDOR, that included the two Norwegian companies Brødrene Aa AS and FiReCo AS in the above list. The assistance of DNV-SAFEDOR and all other project partners is greatly acknowledged.
Sammanfattning

Nya alternativa fartygskonstruktioner bland annat i brännbara lättviktsmaterial kan nu utvecklas. Det har blivit möjligt sedan SOLAS (International Convention for the Safety of Life at Sea), det internationella regelverket för säkerhet på fartyg, för några år sedan införde möjligheten till funktionsbaserad dimensionering. SOLAS innehåller bestämmelser om hur fartyg ska vara konstruerade för att vara säkra och omfattar allt från brandskydd till stabilitet. Funktionsbaserad dimensionering av brandskyddet kräver bland annat en analys av möjliga brandförlopp i ett visst utrymme, den s.k. ”dimensionerande branden”.

Mycket lite finns idag gjort för att definiera dimensionerande bränder ombord på fartyg. I det här projektet fokuserades på brand i passagerarhytter och vad som händer om olika tekniska system inte fungerar som de ska, till exempel att en hyttfdör stängs inte stängts, att hyttfönstret går sönder eller att sprinklersystemet inte aktiverar. Sådana antaganden görs normalt i en händelseträdsanalys men de praktiska konsekvenserna av dessa ”fel-funktioner” har aldrig tidigare provats.

Två fartygshytter byggdes i en ytterstruktur av plastkomposit

Två fartygshytter och en korridor i brandteknisk klass B-15 byggdes i en brandisolerad ”fartygsöverbyggnad” av plastkomposit. En huvudfråga i projektet var hur ytterstrukturen påverkas vid brandförloppen och om utvändig brandspridning kan förhindras med ett utvändigt sprinklersystem.

Försöksupptäckningen var mycket realistisk och inkluderade inte bara helt autentiska och moderna inredningsmaterial och lös inredning utan också ett ventilationssystem, ett sprinklersystem (vattendimma genom högtryck) och ett branddetektionssystem. Marknadsledande företag levererade och installerade systemen.

Totalt genomfördes fem försök där brand anlades i en av hytterna och två försök där brand genom ett hyttfönster simulerades med en strategisk placerad balja med heptan.

Många intressanta resultat

I samtliga fäll detekterades branden av branddetektionssystemet efter drygt en minut. Sprinklersystemet aktiverades efter mellan 2,5 och 3 minuter och trots det låga vattenflöden kontrollerade systemet branden och begränsade både brandskadorn och brandgasutveckling.

Även om sprinklersystemet är ur funktion självslocknar branden om hyttfdörren är stängd. Brandskadorn blir relativt begränsade. Däremot uppstår en miljö i hytten som är akut livsfarlig på grund av de toxiska gaser som bildas.


Brandisoleringen på kompositändets undersida, alltså ovanför hytterna, skyddade däcket från omfattande brandskador och brandisoleringen på kompositskivor insida skyddade ytterväggarna. Brandisoleringen var av ett isoleringsmaterial som är särskilt utvecklat för att vara lätt. Isoleringens tjocklek var 100 mm. Brandisoleringen på
kompositdäckets översida (’hyttgolvet’) var tunnare, endast 20 mm och klarade inte att
skydda däcket. Detta resulterade i en omfattande brandskada på kompositdäcket.

Vid övertändningsförsök bildades höga koncentrationer saltsyra (HCl) eftersom hyttens
väggar och tak hade ett (visserligen tunt) ytskikt som innehåller PVC. I ett något senare
skede av brandförloppet bidrog även golvmattans innehåll av PVC till höga koncentra-
tioner av saltsyra i brandröken.

Två försök utfördes där brandspridning på utsidan av ”fartygsöverbyggnaden” simulera-
des. Här förhindrades brandspridningen effektivt av det utvändiga sprinklersystemet även
med relativt låga vattenflöden.

**Hög brandsäkerhet med tänkbara förbättringsåtgärder**

Om alla säkerhetssystem fungerar som tänkt är brandsäkerheten mycket hög på ett
passagerarerefartyg. Risken för brand- och brandgasspridning utanför den fartygshytter där
branden startar är låg. Om däremot inte säkerhetssystemen fungerar beror brandskyddet
på inredningsmaterialen brandegenskaper. Här visar erfarenheterna från projektet att flera
saker kan förbättras.

Trots att både inredningsmaterial och löss inredning är reglerade i SOLAS innehåller de
tillräckligt med energi för en snabb och mycket kraftig övertändning. Madrasser och
bäddutrustning med bättre antändningsegenskaper och lägre energinnehåll skulle öka
brandsäkerheten radikalt. Försöken visar också att golvmattan i hytten står för en stor del
av brandbelastningen och i högsta grad bidrar till den kraftiga branden. Golvmattan i
korridoren möjliggör också brandspridning till andra utrymmen. De invändiga ytskikt på
väggar och tak var mycket tunna och bidrar inte lika mycket till den totala brand-
belastningen som golvmattan. Däremot innehöll ytskikten även på väggarna och tak PVC
som gör att HCl bildades i ett tidigt skede av brandförloppet.

Övertaksutrymmen sprinklas normalt inte. Ett sprinklersystem skulle kunna ha förhindrat
eller fördröjt tiden till brandspridning mellan hytterna och brandexponeringen mot däcket
ovanför hytterna skulle ha blivit lägre.

Projektet finansierades av VINNOVA under deras Sjösäkerhetsprogram tillsammans med
Stena Rederi AB. Ett stort antal företag bidrog också med både kunskap, material, utrust-
ning och arbetstid för att göra försöken möjliga.

**Sökord:** Fartyg, fartygshytter, fullskaldeförsök, brand, brandskydd, vattendimma,
sprinkler.
1 Background and scope of the project

1.1 Background

There is a world-wide interest of using lightweight construction materials for ship-building. The use of combustible lightweight materials, previously prohibited by the SOLAS requirement for "steel or equivalent" construction material, is now possible through the new (2002) Regulation 17 on "Alternative design and arrangements". However, the (equivalent) safety level has to be demonstrated and the fire tests described within this report involving combustible composites should be seen in this light.

The fire tests are also providing input for a specific design case where the ship owner STENA is preparing for a RoPax vessel with a superstructure built in composite.

1.2 Scope of the project

The main idea for the project was to design fire tests that resemble possible fires in a RoPax cabin. The objectives were twofold; one aim was to study the fire development and the design fire, the influence sprinkler, ventilation, materials. The other aim was to evaluate the behaviour of a composite structure under realistic fire conditions, also with all active safety systems out of order.

For this purpose, a two bed cabin and corridor "RoPax replicate", surrounded by a properly insulated Glass Fibre Reinforce Plastic (GFRP) composite superstructure were built in the SP fire lab in Borås, Sweden. An open deluge (drencher) sprinkler system was installed on the outside of the superstructure in order to evaluate fire protection of the "hull".

The comprehensive large-scale fire test series were made possible by joint cooperation in the two Swedish research projects concerning lightweight ship building, LASS (Lightweight construction applications at sea, www.lass.nu) and DIBS (Design basis for fires at sea), both funded by VINNOVA. Both projects involves important industry partners that took active part and provided material, working hours and financing essential for the unique set of experiments reported here. Furthermore, the DNV-led subtask within the EU-project “SAFEDOR” (www.safedor.org) was a notable partner that supplied both material and advice for the construction of the cabin.
The fire test set-up

2.1 General

The fire test set-up consisted of two passenger cabins connected to a corridor, built inside a fire insulated Glass Fibre Reinforced Plastic (GFRP) composite superstructure. Detailed drawings are presented in Appendix A and photos showing the construction process in Appendix C.

Each of the cabins measured 4300 mm (L) by 2995 mm (W), i.e. the gross internal inside area was 12.9 m². The ceiling height was 2100 mm and the corresponding volume of each of the cabins 27.0 m³. Inside the cabins, walls forming a ‘bathroom module’ was constructed, however, the actual interior of this unit was not installed, neither was the door.

Each of the cabins had a window opening that measured 1000 mm (H) by 1000 mm (W) with a free opening of 880 mm (H) by 880 mm (W).

The corridor measured 5950 mm (L) by 1200 mm (W) and was open in one end, the other end was blocked.

The void space that was formed above the ceiling of the cabins and the corridor and the fire insulated GFRP composite superstructure was sealed at the open sides using 20 mm Rockwool® insulation with an outer layer of 8 mm MasterBoard® non-combustible wall boards.

2.2 The cabins and the corridor

The cabins and the corridor was constructed by Isolamin sandwich panels with a core of mineral wool with galvanised metal sheeting, refer to Table 1. The panels had a decorative vinyl coating, with a thickness of 150 µm on both the inner and the outer sides. The coating contained PVC.

Table 1 The wall and ceiling panels for the cabins and corridor.

<table>
<thead>
<tr>
<th>Item</th>
<th>Article no.</th>
<th>Panel weight [kg/m²]</th>
<th>Thickness [mm]</th>
<th>Fire rating</th>
<th>Sound reduction [dB Rw]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall panels</td>
<td>33C50</td>
<td>21.1</td>
<td>50</td>
<td>B-15</td>
<td>33</td>
</tr>
<tr>
<td>Wall panels*</td>
<td>33C25</td>
<td>13.8</td>
<td>25</td>
<td>B-15</td>
<td>29</td>
</tr>
<tr>
<td>Ceiling panels</td>
<td>IFC50</td>
<td>11.4</td>
<td>50</td>
<td>B-15</td>
<td>48**</td>
</tr>
</tbody>
</table>

*) Each of the cabin-to-cabin walls were constructed by panels with a nominal thickness of 25 mm, separated by 25 mm, in order to achieve the sound reduction desired in practice.

**) Estimated cabin-to-cabin.

The walls that formed the ‘bathroom module’ was constructed from nominally 12 mm thick Promatect® non-combustible wall boards. The outer dimensions of the module was 1800 mm (L) by 1200 mm (W). The module had no door, but it was fitted with a ventilation extract vent and twelve Ø=25 mm holes were drilled at the bottom part to simulate the ventilation opening of a door. For Test 4b) the outer surfaces was covered by the decorative vinyl coating used on the other cabin walls.
2.3 The cabin doors

Each of the cabins were fitted with a steel door, rated B-15. With the door open, the free opening of the cabin doorway was 2014 mm (H) by 750 mm (W). The gaps around the door blade, except at the bottom part, were sealed with silicone strips.

The doors were supplied by Hellbergs International AB.

2.4 The GFRP composite superstructure

The composite superstructure was constructed from sandwich panels made of glass fibre reinforced plastic (GFRP) on a core of Divinycell. The panels were produced at Kockums using infusion technology. The resin used was a polyester. The lower side of the decks and the bulkheads were made of Divinycell H80 with a thickness of 50 mm and two layers of glass fibre (0°/90° 600 g/m²) on each side.

The upper side of the decks had two layers of glass fibre (0°/±45°/90° 850 g/m²).

The panels were laminated on site to a superstructure with outer dimensions of 6534 mm (L) by 6054 mm (W) by 2650 mm (H). The height of the bulkhead with the window openings was 4200 mm. No bulkheads were used on two of the sides, instead the upper deck was supported by a wooden structure, see Figure 2 - Figure 4.
Two 1000 mm by 1000 mm window openings were made in the superstructure and openings with the same dimensions were cut in the B-class structure. The inside perimeter of the openings were fire insulated with 25 mm of mineral wool insulation and lined with an outer layer of nominally 1.5 mm steel sheet. The window was installed up against a 30 mm vertical edge, at a horizontal distance of 50 mm from the outside.

The free open area of the window openings, were 880 mm (W) by 880 mm (H), respectively. The gap measured from the outside walls of the cabins and the insulation material was 200 mm.

![Figure 2](image1.jpg) ![Figure 2](image2.jpg) ![Figure 2](image3.jpg) ![Figure 2](image4.jpg)

**Figure 2** The assembling of the GFRP composite superstructure.
Figure 3  An overview of the GFRP composite superstructure.

Figure 4  Another view of the GFRP composite superstructure that shows how the upper deck was supported on this side and the back side with a wooden structure. It may also be noted how the ceiling void space that was formed above the ceiling of the cabins and the corridor was sealed. The small opening in the panels is an observation window.
2.5 Fire insulation of the GFRP composite superstructure

The underside of the top deck and the inside of the bulkheads of the superstructure were fire insulated with Thermal Ceramics FireMaster®. The fire insulation blankets was applied in four layers with aluminium foil in between and the overall, nominal thickness was 100 mm. The insulation was fixed with anchor pins and friction fit washers to the composite superstructure. The installation was made in accordance with the manufacturer’s data sheets [1, 2].

An outer layer of aluminium foil was installed on the fire insulation on the bulkheads, but not on the fire insulation on the underside of the deck.

The nominal area weight of the insulation is 6.85 kg/m² (applied to a flat area).

The fire insulation system has previously been fire tested for load bearing composite GRE/PVC sandwich decks and bulkheads to a 60-minutes fire rating and hold an MED certificate.

The fire insulation was supplied and installed by Thermal Ceramics Europe.
2.6 The floating floor

A floating floor was installed at the top of the bottom deck, consisting of a single layer of 1200 mm by 600 mm Rockwool® floor plates, having a nominal thickness of 20 mm covered by 2000 mm by 1000 mm aluminium plates with a nominal thickness of 2 mm.

The aluminium plates were installed edge-to-edge and glued to 90 mm wide steel strips, having a nominal thickness of 1.5 mm that was centred underneath the gap.

The insulation material had a nominal density of 150 kg/m³, a heat transfer coefficient (λ) of 0.037 W/mK and thermal resistance (R) of 0.50 m²K/W.

The material for the floating deck was provided by Brødrene Aa AS.

2.7 Floor covering material

The floor of the cabin and the corridor was covered by a homogenous floor carpet made from Polyvinylchloride (PVC), reinforced by Polyurethane (PU). The covering had an overall thickness of 2.0 mm and an area weight of 3.1 kg/m².

The carpet was denoted “Granit 2.0 mm”, the colour was light grey and it was provided by Tarkett AB.

2.8 The ventilation system

In both cabins, a Monovent air supply unit including heater element was installed. These units are designed to be mounted above a false ceiling.

![Figure 6](image)

Figure 6 The Monovent air supply unit at the void space between the ceiling of the cabins and the superstructure and the inlet at the ceiling of Cabin A.

The volumetric air supply was 70 l/s through the ceiling-mounted unit and the air outlet rate was 20 l/s through the lower part of the bathroom module. The ventilation system was shut down upon fire detection.

The ventilation equipment was provided by Callenberg Fläkt Marine AB.
2.9 The interior material

The interior consisted of the following items:

- Two Pullman type bunk beds. The bunk beds were fitted with mattresses and bedding material.
- Mattresses and bedding material associated with the bunk beds.
- A small table positioned below the window of cabin.
- A chair positioned in front of the table.
- A hat rack.
- Windows curtains.
- Light fixtures.
- Personal belongings and luggage.

The items are described in detail in the sub-sections below.

2.9.1 The Pullman type bunk beds

The Pullman type bunk beds were constructed from aluminium and was purchased from SBA Interior AB in Finland.

![Image of the cabin interior](image)

Figure 7 The cabin interior depicted prior to Test 1.

2.9.2 Mattresses and bedding material

Given below is a list of measures and weight, respectively of the mattresses and the bedding material that was used. Most of the material was used and were delivered by STENA, however, some were bought from local suppliers.
Table 2  The measures, weights and suppliers of the mattresses and the bedding material that was used in the tests.

<table>
<thead>
<tr>
<th>Item</th>
<th>Measures (mm)</th>
<th>Weight (g)</th>
<th>Supplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foam mattress with cover</td>
<td>780 (W) by 2030 (L)</td>
<td>6400 g</td>
<td>STENA</td>
</tr>
<tr>
<td></td>
<td>by 110 (T)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spring mattress</td>
<td>900 (W) by 2000 (L)</td>
<td>Total: 12620 g.</td>
<td>STENA</td>
</tr>
<tr>
<td></td>
<td>by 120 (T)</td>
<td>Combustibles: 4480 g.</td>
<td></td>
</tr>
<tr>
<td>Bedding mattress</td>
<td>900 (W) by 2000 (L)</td>
<td>1970 g</td>
<td>STENA</td>
</tr>
<tr>
<td>Sheet</td>
<td>2500 by 1500</td>
<td>520 g</td>
<td>Hemtex</td>
</tr>
<tr>
<td>Quilt</td>
<td>1300 (W) by 1900 (L)</td>
<td>1250 g</td>
<td>STENA</td>
</tr>
<tr>
<td>Pillow</td>
<td>500 by 400 by 140 (T)</td>
<td>570 g</td>
<td>STENA</td>
</tr>
<tr>
<td>Quilt bag/cover</td>
<td>1500 (W) by 2500 (L)</td>
<td>620 g</td>
<td>Jysk Bäddlager</td>
</tr>
<tr>
<td>Pillowcase</td>
<td>500 (W) by 600 (L)</td>
<td>80 g</td>
<td>Jysk Bäddlager</td>
</tr>
</tbody>
</table>

One of the spring mattresses was dismantled and the combustibles were weighted separately in order to determine the exact weight of the combustible material in relation to the non-combustible material.

The width of the spring mattresses was such that the internal cross sectional steel bars of the mattress had to be cut in order to fit the mattress in the Pullman bunk bed. The foam mattresses were not modified.

The spring mattress were fitted with a bedding mattress. The foam mattress was used without any bedding mattress.

2.9.3  The table and the chair

The window table was mounted directly under the window openings, respectively, of the cabins with the top surface 715 mm above floor level. The table measured 600 mm by 600 mm a thickness of 48 mm. The table was constructed from massive wood and the overall weight was 14 430 g.

One chair was used in the cabins, respectively. The overall weight of the chair was 5500 g and the weight of the combustibles was estimated to be 1500 g.

2.9.4  The hat rack

One hat rack, respectively, was installed in the cabins. The hat rack measured 1000 mm (L) by 200 mm (W) by 200 mm (H) and the measured weight was 6400 g.

The hat rack was mounted on the long side wall, opposite the bathroom module and 240 mm below the ceiling.

2.9.5  Decorative wood bars and window curtains

Decorative wood bars were installed inside the cabins, respectively, on the long side wall opposite the bathroom module.

Three long (150 mm) wood bars were installed directly under the hat rack, at a vertical distance of 130 mm and three short (340 mm) were installed in front of the Pullman bunk bed. Total mass about 3.7 kg.
Each cabin was fitted with two window curtains. The curtains measured 750 (W) by 1100 mm (L) mm and the total weight was $2 \times 244 \text{ g} = 488 \text{ g}$.

### 2.9.6  The light fixtures

Two light fixtures of type “Hövik Casa Marin” were mounted in each of the cabins and two light fixtures of the same type inside the corridor. The light fixtures were built into the ceiling and protected inside a box made from 50 mm Rockwool®, sized 280 mm by 570 mm by 140 mm dimensions, glued together and attached to the outside of the B-class ceiling panels with Sikaflex 291, see photos in Figure 8.

![Figure 8](image_url)

**Figure 8**  The construction of the ‘box’ of Rockwool® fire insulation that covered the part of the light fixtures that was on the outside of the cabin and corridor ceiling.

### 2.9.7  Luggage

The luggage consisted of four suitcases; two large and two medium sized, with the following measures and weights:

**Large suitcase:** Size 700 mm (L) by 550 mm (H) by 260 mm (W). The internal volume given by the manufacturer was 85 L and the nominal weight 6290 g.

**Medium sized suitcase:** Size 620 mm (L) by 420 mm (H) by 250 mm (W). The internal volume given by the manufacturer was 60 L and the nominal weight 4940 g.
The suitcases were mainly made from plastic, but contained parts of metal (aluminium and steel) and nylon.

The suitcases were filled with clothes made from cotton or Polyester and the total weight was determined:

Large suitcase with clothes: 14 270 g, i.e. the weight of the clothes was 7980 g.
Medium sized suitcase with clothes: 10 590 g i.e. the weight of the clothes was 5650 g.

2.9.8 Personal belongings

Four winter coats were hanged in the hat rack.

The coats were of mid-length, had a hood and was marked “Rappson®”. The outer layer of the coats were made from 100% Polyamide and the insulation and liner from 100% Polyester.

The weight of the coats were 1140 g each, i.e. the total weight of the four coats were 4560 g.
2.9.9 An analysis of the fire load inside Cabin A

The fire load of a compartment is the sum of energy that can be released in a fire. It can be estimated by knowing the mass of organic materials in the cabin together with the effective heat of combustion, i.e. the amount of energy released per mass burnt material. The total fire load installed in Cabin A is summarised in Table 3. The values of Heat of Combustion are effective values coming from confidential test results and from published data in [3]. There is uncertainty in some of the heat of combustion values and they can also depend on conditions during combustion.

The resulting total fire load of 3 GJ is a reasonable estimate for a cabin of this type with 3-4 passengers. Additional luggage, liquors and a TV set have not been considered.

Table 3 An analysis of total fire load in Cabin A.

<table>
<thead>
<tr>
<th>Material/Object</th>
<th>Combustible mass (kg)</th>
<th>Heat of combustion (MJ/kg)</th>
<th>Fire load (MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walls (PVC foil)</td>
<td>6.1</td>
<td>14.9</td>
<td>91</td>
</tr>
<tr>
<td>Ceiling (PVC foil)</td>
<td>2.8</td>
<td>14.9</td>
<td>41</td>
</tr>
<tr>
<td>Floor (PVC carpet)</td>
<td>38.1</td>
<td>14.9</td>
<td>567</td>
</tr>
<tr>
<td>Foam mattresses</td>
<td>6.4</td>
<td>27.0</td>
<td>173</td>
</tr>
<tr>
<td>Spring mattresses</td>
<td>13.4</td>
<td>20.0</td>
<td>269</td>
</tr>
<tr>
<td>Bedding mattresses</td>
<td>5.9</td>
<td>20.0</td>
<td>118</td>
</tr>
<tr>
<td>Sheets</td>
<td>2.1</td>
<td>10.0</td>
<td>21</td>
</tr>
<tr>
<td>Quilts</td>
<td>5.0</td>
<td>15.0</td>
<td>75</td>
</tr>
<tr>
<td>Quilt cases</td>
<td>2.5</td>
<td>10.0</td>
<td>25</td>
</tr>
<tr>
<td>Pillows</td>
<td>2.3</td>
<td>15.0</td>
<td>34</td>
</tr>
<tr>
<td>Pillowcases</td>
<td>0.3</td>
<td>10.0</td>
<td>3</td>
</tr>
<tr>
<td>Chair</td>
<td>1.5</td>
<td>18.0</td>
<td>27</td>
</tr>
<tr>
<td>Table</td>
<td>14.4</td>
<td>15.0</td>
<td>216</td>
</tr>
<tr>
<td>Hat rack</td>
<td>1.0</td>
<td>15.0</td>
<td>15</td>
</tr>
<tr>
<td>Decorative bars (4470 mm)</td>
<td>3.7</td>
<td>15.0</td>
<td>55</td>
</tr>
<tr>
<td>Coats</td>
<td>4.6</td>
<td>23.0</td>
<td>105</td>
</tr>
<tr>
<td>Large suitcases (PE)</td>
<td>12.2</td>
<td>43.6</td>
<td>532</td>
</tr>
<tr>
<td>Medium suitcases (PE)</td>
<td>9.8</td>
<td>43.6</td>
<td>427</td>
</tr>
<tr>
<td>Large suitcases (clothes)</td>
<td>16.0</td>
<td>10.0</td>
<td>160</td>
</tr>
<tr>
<td>Medium suitcases (clothes)</td>
<td>11.3</td>
<td>10.0</td>
<td>113</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>159</strong></td>
<td>--</td>
<td><strong>3 070</strong></td>
</tr>
</tbody>
</table>
2.10 The fire detection system

Different fire detection techniques and fire detectors were used in the tests. The following type detectors were installed, here listed with the intent of the choice.

Table 4 The type of fire detectors that was installed in Cabin A.

<table>
<thead>
<tr>
<th>No.</th>
<th>Type of detector</th>
<th>Intent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Combined heat and smoke (ionisation) detector.</td>
<td>Historically the most common type detector on board passenger ships.</td>
</tr>
<tr>
<td>2</td>
<td>Combined heat and smoke (optical) detector.</td>
<td>Presently the most common type detector on board passenger ships.</td>
</tr>
<tr>
<td>3</td>
<td>Smoke (dual optical) detector.</td>
<td>Expected to be the most common type detector on board passenger ships in the near future.</td>
</tr>
<tr>
<td>4</td>
<td>As per no. 2, with a recessed installation plate.</td>
<td>Interest to investigate: 1) if the recessed installation influence the activation time, both with regard to detection of heat and smoke, 2) if the passive fire protection is deteriorated by the recessed installation plate.</td>
</tr>
<tr>
<td>5</td>
<td>Sampling type detector.</td>
<td>Could be used for environments where traditional detectors are not possible to use.</td>
</tr>
</tbody>
</table>

Additional fire detectors and fire detection techniques were used, however, the information is not published within this report. The fire detection system was supplied and installed by Consilium Fire & Gas AB.

Figure 11 The different type of fire detectors installed in the ceiling of Cabin A.
2.11 The high-pressure water mist system

Two nozzles were installed inside Cabin A, one nozzle positioned close to the centre area of the cabin (2100 mm from the short side wall with the window opening) with an activation temperature of 57°C, and the other just inside the window opening (250 mm from the short side wall) with an activation temperature of 93°C. Additionally, two nozzles were installed at the centreline of the corridor with a spacing of 4000 mm with activation temperatures of 57°C. See also drawing in Appendix A.

The nozzle positioned at the centre area of the cabin and the two nozzles inside the corridor had a K-factor of 0.8 (metric) and a nominal operating temperature of 57°C. The nozzle just inside of the window opening had a K-factor of 0.8 (metric) and a nominal operating temperature of 93°C.

The nozzles used in the tests has been tested according to IMO Resolution A.800(19) and is approved by Det Norske Veritas, Bureau Veritas and other classification societies.

![Image of the high-pressure water mist nozzle at the ceiling of Cabin A and the installation of the system pipe-work in the void space above the cabins and corridor.]

The system pipe-work consisted of nominally 12 mm stainless steel pipes and was connected to a high-pressure pump unit. The pipe-work was pressurized with a pilot pressure of 25 bar and as soon as the first nozzle activated, the pressure loss in the system provided a signal to start the pump unit. The system operating pressure was 100 bar. The delay time from the activation of the first nozzle until full system pressure was between 18 and 24 seconds, which reflects the delay time of an actual installation.

Two “dummy” nozzles were installed inside Cabin B, in the same fashion as described above but were not connected to the pipe-work.

The nozzles, pipe-work and the pump unit was supplied and installed by Ultra Fog AB.

2.12 The drencher system

An open deluge (drencher) sprinkler system was installed on the outside of the superstructure.

TYCO Model WS™, 5.6 K-factor (80.6 L/min/bar$^{1/2}$), horizontal sidewall sprinklers were used. This type of sprinkler can be used as interior protection of window glazing but can also be used as an open sprinkler for exposure fire protection [4].
The sprinklers are normally fitted with fast response glass bulbs but for these tests the glass bulbs were removed and the sprinklers were manually activated.

Four sprinklers were installed on a horizontal DN25 (1”) branchline at a c-c of 2000 mm. The sprinklers were orientated with the deflector towards the outside of the superstructure, such that the horizontal distance from the deflector to the vertical surface was 15 mm, see Figure 13.

Figure 13  The position and orientation of the sprinklers of the drencher system relative to the superstructure.

The sprinklers were installed at a vertical height of 3700 mm above floor level, i.e. each sprinkler covered an area of 14.8 m². The water flow rate was adjusted such that the nominal discharge density over the vertical surface below the sprinklers equalled 2.5 L/min/m², i.e. the nominal flow rate of each of the sprinklers were 37.5 L/min. This corresponded to a water pressure of 0.2 bar.

The sprinklers were supplied by TYCO Building Services Products (Sweden).
3 Measurements and instrumentation

3.1 Heat Release Rate measurements

The test set-up was positioned under the Industry Calorimeter, a large hood connected to an evacuation system capable of collecting all the combustion gases produced by the fire. The hood is 6 m in diameter with its lower rim 7.2 m above the floor. A rectangular fibreglass "skirt", hanging from the lower rim of the hood, was used to increase the gas collecting capacity of the hood. In the duct connecting the hood to the evacuation system, measurements of gas temperature, velocity and gas concentration of CO₂, CO and O₂ are made, see Figure 14.

![The Industry Calorimeter was used to measure the Heat Release Rate from the fires.](image)

Based on these measurements and the theory of oxygen depletion the time-resolved fire heat release rate (HRR) can be calculated. The resulting HRR is plotted in Appendix B, Figure 64.

3.2 Temperature measurements

3.2.1 Gas temperature measurements, thermocouple trees

The gas temperatures inside the cabins and the corridor was measured with (Type K) thermocouples having a diameter of 0.5 mm and a welded measuring junction. The thermocouple tree inside the cabins was positioned along the centreline of the short side wall, 2750 mm from this wall. The thermocouple trees in the corridor was positioned at the centreline of the corridor, at the centreline of the doorway opening, respectively.
The thermocouples on the tree were positioned the following vertical distances from the ceiling: 100 mm, 250 mm, 500 mm, 750 mm, 1000 mm and 1400 mm. See Table 5 - Table 7 for details.

For the thermocouple tree inside the cabins, small angle iron shields were positioned above each measurement point to minimize wetting of the thermocouples by direct water spray impingement from the high-pressure water mist system. For the thermocouple tree in the corridor, no such arrangement was considered necessary.

Gas temperatures were also measured close to the glass bulb of the individual water mist nozzles and at the outside of the window opening.

### 3.2.2 Surface temperature measurements

The surface temperatures on the outside of the B-class divisions that formed the cabins and the corridor were measured with thermocouples that were spot-welded directly to the outer steel sheets.

The surface temperatures on the inside of the laminate of the composite superstructure was measured with wire thermocouples. These thermocouples were inserted from the outside, through 4 mm holes. After the insertion of the thermocouples, the holes were filled with FireStop® silicone.

Additionally, the surface temperatures under the floor carpet (spot-welded on the aluminium floor) and on the composite deck (positioned under the Rockwool® fire insulation) were measured.

These measurements were conducted at two different positions seen from a top view, firstly at a position that correlated with the point of fire ignition and, secondly at a point at the centreline of the cabin.

The surface temperatures on the outside of the superstructure were measured at two different positions outside the window opening, respectively. The intent was to record the surface temperatures caused by flames out from the window openings.

Type K thermocouples having a diameter of 0.5 mm were used for all measurements.
Table 5  The instrumentation and the associated measurements channels for Cabin A.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inside Cabin A</strong></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>Gas temperature 100 mm below ceiling</td>
</tr>
<tr>
<td>22</td>
<td>Gas temperature 250 mm below ceiling</td>
</tr>
<tr>
<td>23</td>
<td>Gas temperature 500 mm below ceiling</td>
</tr>
<tr>
<td>24</td>
<td>Gas temperature 750 mm below ceiling</td>
</tr>
<tr>
<td>25</td>
<td>Gas temperature 1000 mm below ceiling</td>
</tr>
<tr>
<td>26</td>
<td>Gas temperature 1400 mm below ceiling</td>
</tr>
<tr>
<td><strong>Inside corridor (outside doorway opening)</strong></td>
<td></td>
</tr>
<tr>
<td>27 - 32</td>
<td>Positions as per above</td>
</tr>
<tr>
<td><strong>Inside Cabin A</strong></td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>Gas temperature close to water mist nozzle (A-1)</td>
</tr>
<tr>
<td>34</td>
<td>Gas temperature close to water mist nozzle (A-2)</td>
</tr>
<tr>
<td>35</td>
<td>Gas temperature at centreline of window opening, 100 mm below top</td>
</tr>
<tr>
<td>36</td>
<td>Gas temperature at centreline of window opening, 250 mm below top</td>
</tr>
<tr>
<td>37</td>
<td>Gas temperature at centreline of window opening, 500 mm below top</td>
</tr>
<tr>
<td>38</td>
<td>Gas temperature at centreline of window opening, 750 mm below top</td>
</tr>
<tr>
<td>39</td>
<td>Plate Thermometer at the floor</td>
</tr>
<tr>
<td>40</td>
<td>Plate Thermometer at the floor (corridor)</td>
</tr>
<tr>
<td><strong>Inside Cabin A: Along centreline, 900 mm from short side wall</strong></td>
<td></td>
</tr>
<tr>
<td>41</td>
<td>Surface temperature on composite superstructure (top deck)</td>
</tr>
<tr>
<td>42</td>
<td>Surface temperature on outside of the B-class division</td>
</tr>
<tr>
<td>43</td>
<td>Gas temperature, 50 mm below insulation of the composite superstructure (top deck)</td>
</tr>
<tr>
<td>44</td>
<td>Surface temperature under floor carpet, on top of the floating deck</td>
</tr>
<tr>
<td>45</td>
<td>Surface temp. on composite superstructure (bottom deck), i.e. under floating deck</td>
</tr>
<tr>
<td><strong>Inside Cabin A: 425 mm from the long side wall, 900 mm from short side wall</strong></td>
<td></td>
</tr>
<tr>
<td>46 - 50</td>
<td>Positions as per above</td>
</tr>
<tr>
<td><strong>Inside Cabin A</strong></td>
<td></td>
</tr>
<tr>
<td>51</td>
<td>Surface temp. on outside of superstructure, 105 mm above window opening</td>
</tr>
<tr>
<td>52</td>
<td>Surface temp. on outside of superstructure, 500 mm above window opening</td>
</tr>
<tr>
<td>53</td>
<td>Surface temp. on outside of B-class division (T=25 mm), 100 mm below ceiling</td>
</tr>
<tr>
<td>54</td>
<td>System water flow rate (drencher system)</td>
</tr>
<tr>
<td>55</td>
<td>Not in use</td>
</tr>
<tr>
<td>56</td>
<td>Gas temperature at the bi-directional probe at the doorway opening</td>
</tr>
<tr>
<td>57</td>
<td>Cabin pressure (static pressure). Probe 50 mm below ceiling</td>
</tr>
<tr>
<td>58</td>
<td>Oxygen concentration, 500 mm below ceiling</td>
</tr>
<tr>
<td>59</td>
<td>Carbon Monoxide concentration, 500 mm below ceiling</td>
</tr>
<tr>
<td>60</td>
<td>Carbon Dioxide concentration, 500 mm below ceiling</td>
</tr>
</tbody>
</table>

Note: Channels 38 to 40 moved to Cabin B during the final fire test.
<table>
<thead>
<tr>
<th>Channel</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inside Cabin B</td>
<td></td>
</tr>
<tr>
<td>61</td>
<td>Gas temperature 100 mm below ceiling</td>
</tr>
<tr>
<td>62</td>
<td>Gas temperature 250 mm below ceiling</td>
</tr>
<tr>
<td>63</td>
<td>Gas temperature 500 mm below ceiling</td>
</tr>
<tr>
<td>64</td>
<td>Gas temperature 750 mm below ceiling</td>
</tr>
<tr>
<td>65</td>
<td>Gas temperature 1000 mm below ceiling</td>
</tr>
<tr>
<td>66</td>
<td>Gas temperature 1400 mm below ceiling</td>
</tr>
<tr>
<td>Inside corridor (outside doorway opening)</td>
<td></td>
</tr>
<tr>
<td>67 - 72</td>
<td>Positions as per above</td>
</tr>
<tr>
<td>Inside Cabin B</td>
<td></td>
</tr>
<tr>
<td>73</td>
<td>Not in use</td>
</tr>
<tr>
<td>74</td>
<td>Not in use</td>
</tr>
<tr>
<td>75</td>
<td>Gas temperature at centreline of window opening, 100 mm below top</td>
</tr>
<tr>
<td>76</td>
<td>Gas temperature at centreline of window opening, 250 mm below top</td>
</tr>
<tr>
<td>77</td>
<td>Gas temperature at centreline of window opening, 500 mm below top</td>
</tr>
<tr>
<td>78</td>
<td>Gas temperature at centreline of window opening, 750 mm below top</td>
</tr>
<tr>
<td>79</td>
<td>Not in use</td>
</tr>
<tr>
<td>80</td>
<td>Not in use</td>
</tr>
<tr>
<td>Inside Cabin B: Along centreline, 900 mm from short side wall</td>
<td></td>
</tr>
<tr>
<td>81</td>
<td>Surface temperature on composite superstructure (top deck)</td>
</tr>
<tr>
<td>82</td>
<td>Surface temperature on outside of the B-class division</td>
</tr>
<tr>
<td>83</td>
<td>Gas temperature, 50 mm below insulation of the composite superstructure (top deck)</td>
</tr>
<tr>
<td>84</td>
<td>Surface temperature under floor carpet, on top of the floating deck</td>
</tr>
<tr>
<td>85</td>
<td>Surface temp. on composite superstructure (bottom deck), i.e. under floating deck</td>
</tr>
<tr>
<td>Inside Cabin B: 425 mm from the long side wall, 900 mm from short side wall</td>
<td></td>
</tr>
<tr>
<td>86 - 90</td>
<td>Positions as per above</td>
</tr>
<tr>
<td>Inside Cabin B</td>
<td></td>
</tr>
<tr>
<td>51</td>
<td>Surface temp. on outside of superstructure, 105 mm above window opening</td>
</tr>
<tr>
<td>52</td>
<td>Surface temp. on outside of superstructure, 500 mm above window opening</td>
</tr>
<tr>
<td>93</td>
<td>Surface temp. on outside of B-class division (T=25 mm), 100 mm below ceiling</td>
</tr>
<tr>
<td>94</td>
<td>Bi-directional probe at window opening, 100 mm below top</td>
</tr>
<tr>
<td>95</td>
<td>Bi-directional probe at doorway opening, 250 mm below top</td>
</tr>
<tr>
<td>96</td>
<td>See Channel 56</td>
</tr>
<tr>
<td>97</td>
<td>See Channel 57</td>
</tr>
<tr>
<td>98</td>
<td>System water pressure (water mist system)</td>
</tr>
<tr>
<td>99</td>
<td>System water pressure (drencher system)</td>
</tr>
<tr>
<td>100</td>
<td>Not in use</td>
</tr>
</tbody>
</table>
Table 7: The instrumentation and the associated measurements channels for the composite superstructure around Cabin B.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front wall</td>
<td></td>
</tr>
<tr>
<td>101</td>
<td>Surface temperature on composite superstructure (top level)</td>
</tr>
<tr>
<td>102</td>
<td>Surface temperature on composite superstructure (top level)</td>
</tr>
<tr>
<td>103</td>
<td>Surface temperature on composite superstructure (top level)</td>
</tr>
<tr>
<td>104</td>
<td>Surface temperature on composite superstructure (mid-height)</td>
</tr>
<tr>
<td>105</td>
<td>Surface temperature on composite superstructure (mid-height)</td>
</tr>
<tr>
<td>Side wall</td>
<td></td>
</tr>
<tr>
<td>106</td>
<td>Surface temperature on composite superstructure (top level)</td>
</tr>
<tr>
<td>107</td>
<td>Surface temperature on composite superstructure (top level)</td>
</tr>
<tr>
<td>108</td>
<td>Surface temperature on composite superstructure (top level)</td>
</tr>
<tr>
<td>109</td>
<td>Surface temperature on composite superstructure (mid-height)</td>
</tr>
<tr>
<td>110</td>
<td>Surface temperature on composite superstructure (mid-height)</td>
</tr>
<tr>
<td>111</td>
<td>Surface temperature on composite superstructure (mid-height)</td>
</tr>
<tr>
<td>Ceiling deck</td>
<td></td>
</tr>
<tr>
<td>112</td>
<td>Surface temperature on composite superstructure (close to front wall)</td>
</tr>
<tr>
<td>113</td>
<td>Surface temperature on composite superstructure (close to front wall)</td>
</tr>
<tr>
<td>114</td>
<td>Surface temperature on composite superstructure (close to front wall)</td>
</tr>
<tr>
<td>115</td>
<td>Surface temperature on composite superstructure (mid-level)</td>
</tr>
<tr>
<td>116</td>
<td>Surface temperature on composite superstructure (mid-level)</td>
</tr>
<tr>
<td>117</td>
<td>Surface temperature on composite superstructure (mid-level)</td>
</tr>
<tr>
<td>118</td>
<td>Surface temperature on composite superstructure (close to corridor)</td>
</tr>
<tr>
<td>119</td>
<td>Surface temperature on composite superstructure (close to corridor)</td>
</tr>
<tr>
<td>120</td>
<td>Surface temperature on composite superstructure (close to corridor)</td>
</tr>
</tbody>
</table>

3.3 Gas concentration measurements
The concentrations of Oxygen (O₂), Carbon Dioxide (CO₂) and Carbon Monoxide (CO) were measured at one position inside Cabin A. The gas sampling point was positioned at the thermocouple positioned 500 mm below the ceiling, i.e. at eye-level inside the cabin, and 2750 mm from the short side wall along the centreline of the cabin.

3.4 FTIR gas measurements
During Test 4b), time resolved gas concentrations for several species in the combustion gases leaving Cabin A was measured using FTIR technique (Fourier Transformed Infra Red). A sampling probe was placed across the corridor doorway, diagonally over the top 100 mm of the opening. The multi-hole probe was constructed to sample uniformly over the 100 mm height.

The gases analysed were: CO₂, CO, HCl, HBr, HF, HCN, NH₃, NO, NO₂ and SO₂. The FTIR was a BOMEM MB 100 spectrometer equipped with a heated gas cell. The spectral resolution used was 4 cm⁻¹ and four spectra were recorded per minute. The smoke gases were continuously sampled to the FTIR with a sampling rate of 4 l/min. A heated ceramic filter was fitted between the probe and the 13 m heated sampling line that led to the FTIR.

The FTIR measurement started 2 min before ignition and continued for approximately 11.5 minutes where the sampling filter and pump had to be removed due to the heat radiation. The measurement results are presented in chapter 7.5.4 and Appendix B.
3.5 Compartment pressure measurements

The compartment pressure was measured close to one of the corners of the cabin, 50 mm below the ceiling, using a Digima Premo 355 differential pressure transducer, having inventory number 700179. The instrument has an accuracy of less than 0.5% of measured value, and a response time from zero to full scale of less than one millisecond.

3.6 System water pressure and water flow rate

The system water pressure of the high-pressure water mist system was measured at the pipe-work grid, using a Transinstrument 2000A pressure transducer, rated 0 – 200 bar.

The water flow was measured by multiplying the K-factor of the high-pressure water mist nozzle with the square root of the measured system pressure.

The system water pressure of the drencher system installed on the outside of the superstructure was measured at the end of the pipe-work, using a Transinstrument 2000A pressure transducer, rated 0 – 10 bar.

The total water flow of the drencher system installed on the outside of the superstructure rate was measured using a Krohne 0 – 2000 L/min flow meter.
4 Fire test programme

4.1 General

The fire tests were conducted under both unventilated and ventilated conditions during a number of failure modes, as per the description given below. The following issues were of interest to investigate:

- The Heat Release Rate (HRR). Note: Measured only for the ventilated fire, as the measurement requires the combustion gases to be collected in the Industry Calorimeter.
- The gas temperatures inside the cabin and in the corridor.
- The surface temperatures on the outside of the B-class divisions.
- The surface temperatures on the composite structure.
- The surface temperatures in the floor construction.
- The fire detection times.
- The efficiency of the high-pressure water mist sprinkler system.
- The likelihood for fire spreading in the floor material.
- The likelihood for fire spreading on the outside of the superstructure.

4.2 Unventilated fires

Test 1: No failure mode

- Door closed.
- Window closed.
- Sprinkler system fully functional.

Comment: This test replicates normal conditions, where the door to the cabin is closed, the window remains intact throughout the fire duration time and the sprinkler systems activates as intended.

The active ventilation system was in operation until fire detection when it was shut down and the exhaust pipe was plugged.

Test 2: One failure mode

- Door closed.
- Window closed.
- Sprinkler system out of function (1).

Comment: If both the door to the cabin is closed and the window remains intact throughout the fire duration time, a fire inside a small and reasonably airtight compartment should become ventilation controlled. This was investigated in the test, where the sprinkler system was malfunctioned.

The active ventilation system was in operation until fire detection when it was shut down and the exhaust pipe was plugged.
4.3 Ventilated fires

Test 3: One failure mode

- Door open (1).
- Window closed.
- Sprinkler system fully functional.

Comment: The fact that the fire was ventilated, i.e. that the door to the cabin was open is in itself a failure mode. Usually, there are automatic door closures to every cabin door.

Test 4a) Two failure modes

- Door open (1).
- Window open (2).
- Sprinkler system fully functional. Note: The nozzle positioned above the window opening was disconnected.

Comment: This test was conducted to determine if the sprinkler (one head) system can prevent fire spread on the outside of the superstructure. Both the doorway and the window opening were open in order to provide as ventilated conditions as possible.

Test 4b): Two failure modes

- Door open (1).
- Window closed.
- Sprinkler system out of function (2).

Comment: In this test, the fire was allowed to develop to flashover. For this particular test, the walls of the bathroom module was fitted with the same surface coating as used on the other walls and FTIR gas concentration measurements were undertaken.

4.4 Fires on the outside of the superstructure

Test 5a): 0.5 m² heptane pool fire tray at the window of Cabin B

In tests 5a) and 5b) the efficiency of drencher system on the outside of the superstructure was investigated. The fire source consisted of a 500 mm by 500 mm fire tray, having a rim height of 250 mm that was positioned just inside the window opening. The fire tray was filled with 12.5 l (50 mm depth) of heptane. In order to ensure that the flames of the fire projected out of the window opening, a small “chamber” was built around the fire tray, consisting of a top ceiling of 2 mm steel and back wall of 20 mm mineral wool insulation. The sides of the chamber remained open, see Figure 15.
In the window opening four thermocouples and a bi-directional probe for flow measurement were installed. (The transmitter for the bi-directional probe of C94 was in this test changed to the transmitter used in C95).

One additional embedded thermocouple (C21 was used), installed at the un-exposed side of the composite panel of the superstructure, at the interface between the insulation and laminate. The thermocouple was installed at the centreline of the window opening, 1000 mm above its top.

The drencher system was started directly after the ignition of the fire and was flowing at 150 l/min, which corresponded to and average density of 2.5 l/min/m², i.e. the nominal flow rate of each of the sprinklers were 37.5 l/min.

The door to Cabin B was closed during the test.

**Test 5b): 0.5 m² heptane pool fire tray at the window of Cabin B**

The same fire test source as in 5a) was used but the drencher system was activated after the fire had got hold on the outside surface.

In addition to the thermocouple (C21) imbedded in the superstructure, one additional measurement position was added on the outside surface, a Plate Thermometer (C22) positioned at the centreline of the opening, 400 mm from the top of the window opening. The front face of the Plate Thermometer was positioned 20 mm from the surface laminate.
5 Fire test procedures

5.1 Conditioning of the mattresses and bedding components

Prior the tests the mattresses were conditioned in a controlled environment to reach steady conditions concerning moisture content (23 ± 2°C, 50 ± 5% RH).

5.2 Fire ignition source

The fires were ignited using a standardized wood crib, wood crib No. 7 according to BS 5852:Part 2 [5] and its ignition instructions. The main crib consists of 18 wood sticks with a length of 80 mm and a square section of 12.5 mm. Inside the main crib, an ignition crib is positioned made up from six sticks with a length of 40 mm and a square section of 6.5 mm. The overall mass of the crib is nominally 126 g. See also Figure 16.

The crib were conditioned for at least 72 h in indoor ambient conditions. Just prior to a test, 1.4 ml of propan-2-ol is gently poured to the centre of the lint. The crib was placed in direct contact with the mattress and ignited by a small torch.

In all cabin tests 1 - 4b) an identical ignition source and procedure were used.

5.3 Fire test procedures

The wood crib was positioned at the lower bunk bed, at the centreline of the bed and 500 mm from the head end of the bed, up against the edge of the pillow. To enhance the fire spread, the bedding material of the head end of the bed was removed and the fabric of the foam mattress was exposed to the ignition source.

The ventilation system, i.e. both the air supply to and from the cabin was shut off upon the operation of the last operating fire detector. This was made in order to keep the operational conditions identical for all detectors.

After ventilation system shut-off, the outlets of the ventilation ducts were immediately plugged with insulation material to prevent the leakage of fire gases.

The sprinkler system (if used) were allowed to automatically activate and the water flow rate was shut off at either five or ten minutes after activation.

The test duration time were different for the individual tests and the specific time was chosen to allow the heat generated by the fire to spread in the superstructure.

5.4 Door fan measurements (cabin air-tightness)

The air-tightness of Cabin A was measured prior the tests using the door-fan test method where the cabin was pressurized using a fan and the pressure difference between the inside of the cabin and the outside was measured and recorded. During the tests, the ventilation air inlet and outlet openings of the cabin was sealed with gaffer tape.

Two test cases were conducted, with and without the gaps around the cabin door sealed with tape. The following air pressure differences (compared to the outside) and air flow rates were measured.
Table 8  The air pressure differences determined during the air-tightness tests of Cabin A and the associated and flow rates.

<table>
<thead>
<tr>
<th>Pressure difference (Pa)</th>
<th>Air flow rate (l/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Door gaps not sealed with tape</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>78</td>
</tr>
<tr>
<td>50</td>
<td>123</td>
</tr>
<tr>
<td>75</td>
<td>164</td>
</tr>
<tr>
<td>98.5*</td>
<td>200</td>
</tr>
<tr>
<td>Door gaps sealed with tape</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>45</td>
</tr>
<tr>
<td>50</td>
<td>76</td>
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<td>75</td>
<td>103</td>
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<td>100</td>
<td>130</td>
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<tr>
<td>125</td>
<td>162</td>
</tr>
<tr>
<td>150</td>
<td>192</td>
</tr>
</tbody>
</table>

*) Maximum capacity of the fan.

It could be concluded that the gaps around the door contributed a lot to the overall tightness of the cabin, however, no attempts were made to trace the other leak ways. For the actual fire test, all gaps around the door were sealed with silicone strips as in end-use and it is likely that the doorway was equally air tight with this approach.

Based on the tests, it could be concluded that the air-tightness was considered comparable to the air-tightness measured in actual passenger ships cabins [6].
6 Fire test results and observations

In the following chapters the main test results and observations are presented. Measurement graphs of temperatures and gas concentrations can be found in Appendix B.

6.1 Test 1

Date: 2007-12-03

The first fire test was conducted with the doors and the window closed and with the sprinkler system fully functional.

The bottom bed on the left hand side was fitted with a foam type mattress and the top bunk bed on the left hand side with a spring mattress. No mattresses were used in the right hand side bunk beds since the fire was expected to be controlled in an early phase.

Fire test chronology
-02:00 Start of measurements.
00:00 Fire ignition.
00:55 White smoke from the pillow, indicating that is heating up.
01:28 The first fire detector (ionisation type) activates.
01:35 The pillow ignites.
02:05 The wood cribs falls to the right.
02:40 Approximately half of the pillow is burning.
02:30 The exposed part of the mattress is on fire.
03:00 The visibility inside the cabin is reduced, the cabin is almost completely filled with light smoke.
03:42 The water mist nozzle at the centre area of the cabin activates.
04:10 Full water mist system pressure.
04:25 The cabin is completely filled with dense, black smoke, however, flames of the fire is visible.
07:45 Small flames are visible through the black smoke.
09:00 No smoke at all is visible in the adjacent cabin.
13:42 The sprinkler system is turned off, ten minutes after the activation.
15:00 The door is opened and it can be concluded that the fire is completely extinguished.
25:00 The measurements are terminated.

Damages and other observations

Almost all of the pillow (approx. 95%) was consumed by the fire and a rectangular area that measured approximately 600 mm (W) by 300 mm (L), i.e. approximately 10% of the mattress was consumed. The quilt was slightly burnt at the edge that faced the point of ignition, but was otherwise undamaged. The surface layer on the long side wall was burnt through in three small spots, in total approximately 3 dm².

The mattress and the bedding material in the top bunk bed was undamaged, the material was only a little sooty and wet by the water spray. The underside of the bottom plate of the upper bunk bed was not damaged, only slightly sooty.

It was observed that only one sprinkler nozzle activated, the nozzle at the centre part of the cabin (nominal activation temperature of 57°C). The nozzle above the window (93°C) did not activate.
Furthermore, it was observed that no smoke spread to the adjacent cabin or the corridor. See Appendix B for temperature graphs.

Figure 16 The interior of Cabin A prior to Test 1.

Figure 17 The fire damages after Test 1. Almost the whole of the pillow and approximately 10% of the mattress was consumed by the fire. Damages to the surface coating on the bulkhead was limited.
6.2 Test 2

Date: 2007-12-04

The second fire test was conducted with the door and the window to the cabin closed. The sprinkler system (both nozzles) were disconnected, i.e. the fire was intended to be ventilation controlled inside the cabin.

The bottom bed on the left hand side was fitted with a foam type mattress and the two top bunk beds on the left and right hand side, respectively, with spring mattresses. No mattress was used in the lower, right hand side bunk bed.

Fire test chronology

-02:00 Start of measurements.
00:00 Fire ignition.
00:58 White smoke from the pillow, indicating that it is heated up.
01:00 The pillow is ignited.
01:15 The first fire detector (ionisation type) activates.
01:50 It is observed that the fabric of the mattress is burning.
02:04 The wood crib has fallen to the left.
02:40 Flames touch the underside of the top bunk bed.
02:55 Approximately half of the pillow is burning.
03:30 The visibility is reduced, the cabin is almost completely filled with grey smoke.
03:50 Almost all of the exposed area of the mattress is burning.
04:25 The cabin is completely filled with dense, black smoke, however, flames of the fire is still visible.
04:45 The cabin is completely black and any further observations of the size of the fire is not possible.
05:00 Very little smoke is leaking from the gaps in the construction above the door.
05:30 No smoke is visible in the adjacent cabin.
16:00 A small degree of smoke is still leaking from the gaps in the construction above the door.
20:00 Smoke is observed in the corridor, but not in the adjacent cabin.
63:00 The high-pressure pump unit is started in order to cool the gases prior to the opening of the door.
64:30 The water flow is stopped.
67:30 The door is opened. No signs of fire is observed and there is very little smoke.
70:00 The measurements are terminated.

Damages and other observations

Almost all of the pillow (more than 95%) was consumed by the fire. The mattress had burnt through in a rectangular area that measured approximately 800 mm (W) by 560 mm (L). An additional area, where the mattress had burnt through halfway measured approximately 800 mm (W) by 250 mm (L). Altogether, approximately 30% of the mattress was consumed. The quilt was slightly burnt at the edge that faced the pointed of ignition position, but was otherwise undamaged.

The surface coating on the panels forming the long side wall was consumed in a pattern that measured 800 mm (W) by 800 mm (H). The surface area immediately to the left of the window opening was consumed in a pattern that measured 1200 mm (H) by 500 mm (W). The total damaged to the wall linings approximated 70 dm².
The surface layer of the ceiling panels were damaged in an area close to the corner that measured approximately 2 dm².

The left hand side curtain was completely consumed and the remains indicated that it had melted. The curtain on the right hand side was undamaged.

The fire detectors were slightly deformed by the heat.

The mattress and the bedding material in the top bunk bed was undamaged, only a little sooty and brittle probably due to the heat exposure. The surface layer on the underside of the bottom plate of the upper bunk bed had burnt away in its whole width and in a length of 900 mm, i.e. the area directly above the position of the fire.

The whole ceiling area of the and area of the walls measured down to the height of the window opening was sooty.

Furthermore, it was observed that no smoke spread to the adjacent cabin and very little spread smoke to the corridor during the test.

See Appendix B for temperature graphs.
Figure 19  The fire damages in Test 2. Almost the whole of the pillow and approximately 30% of the mattress was consumed by the fire. Damages to the surface coating on the bulkheads were relatively severe.

6.3  Test 3

Date: 2007-12-04

The third fire test was conducted with the door to the cabin open. The window was closed and the sprinkler system was fully functional.

The bottom bed on the left hand side was fitted with a foam type mattress and the two top bunk beds on the left and right hand side, respectively, with spring mattresses. No mattress was used in the lower, right hand side bunk bed.

Fire test chronology

-02:00  Start of measurements.
00:00  Fire ignition.
00:53  White smoke from the pillow, indicating that it is heated up.
01:06  The pillow is ignited.
01:20  The first fire detector (ionisation type) activates.
01:55  Flames touch the underside of the top bunk bed.
02:50  Approximately half of the pillow is burning.
02:40  Almost all of the exposed surface of the mattress is burning.
02:59  The water mist nozzle at the centre part of the cabin activates.
03:02  The water mist nozzle above the window opening activates.
03:05  The water mist nozzle at the open end of the corridor activates.
03:18  Full water mist system pressure.
03:40  Black smoke is pushed down and the visibility is reduced. It is not possible to observe any fire due to the smoke.
05:00  The visibility is improved.
05:50  A very small fire in the mattress is observed.
06:45  No fire is observed, the fire is most likely extinguished.
08:00  The sprinkler system is turned off, five minutes after the activation of the
first nozzle.
08:15  The visibility is improved and it can be concluded that the fire is
extinguished.
20:00  The measurements are terminated.

**Damages and other observations**

Almost all of the pillow (approximately 95%) was consumed by the fire. The mattress
had a rectangular hole that measured approximately 700 mm (W) by 700 mm (L) burnt
approximately 1/3 of the thickness of the mattress. Altogether, approximately 10% of the
mattress was consumed. The fabric of the quilt was burnt in an area that measured
450 mm (W) by 200 mm (L) at the part that faced the pointed of ignition position, but
was otherwise undamaged.

No damages to the surface coating of the wall and ceiling panels, in addition to the
damages determined in Test 2 was observed.

About 40% of the left hand side curtain was consumed. The curtain on the right hand side
was undamaged.

The mattress and the bedding material in the top bunk bed was undamaged, only a little
sooty and wet from the water sprays. The surface layer on the underside of the bottom
plate of the upper bunk bed had no additional damage as compared to the damages
determined in Test 2.

Furthermore, it was observed that no smoke spread to the adjacent cabin but a small
portion of the floor was wet by water from the nozzle in the corridor.

See Appendix B for temperature graphs.
Figure 20  Both the water mist nozzles inside the Cabin A as well as one of the nozzles inside the corridor activated in Test 3.

Figure 21  The fire damages in Test 3. Almost the whole of the pillow and approximately 10% of the mattress was consumed by the fire. The damages to the surface coating on the bulkheads primarily originated from the previous test.
Figure 22  The fire damages in Test 3 from another viewpoint. The soot at the ceiling primarily originated from the previous test.

6.4  Test 4a)

Date: 2007-12-05

The fourth fire test was conducted with both the door and the window to the cabin open. The sprinkler system was fully functional, except that the nozzle above the window opening was disconnected. The reason for disconnecting this particular nozzle was to challenge the system and investigate whether one cabin nozzle could prevent fire spread through the open window opening.

The bottom bed on the left hand side was fitted with a foam type mattress and the two top bunk bed on the left and right hand side, respectively, with spring mattresses. No mattress was used in the lower, right hand side bunk bed.

Fire test chronology
-02:00  Start of measurements.
00:00  Fire ignition.
00:35  White smoke from the pillow, indicating that it is heated up.
00:55  The pillow is ignited.
01:14  The first fire detector (ionisation type) activates.
01:20  The mattress is burning.
01:45  The flames touch the underside of the upper bunk bed.
01:55  Smoke is escaping the window opening.
02:30  The whole of the exposed area of the mattress is burning.
02:35  The nozzle inside the cabin activates.
02:59  Full water mist system pressure.
03:50 The whole exposed area of the mattress is burning and the fire is quite severe.
04:20 The fire size is reduced.
05:00 Flames still touch the underside of the upper bunk bed.
06:30 Large parts of the exposed area of the mattress has been consumed and the fire size is reduced.
07:20 Still a lot of smoke out through the corridor opening.
08:20 The fire is primarily concentrated to the “edges” of the exposed part of the mattress. The fire size has been reduced and flames are approximately 40 to 50 cm in height. The whole cabin is filled with grey smoke.
12:35 The sprinkler system is turned off, ten minutes after the activation of the first (and only) nozzle.
12:50 The visibility is improved inside the cabin and it can be concluded that the fire is fairly limited.
14:15 The fire is growing in size.
15:00 The fire is manually extinguished.
18:00 The measurements are terminated.

**Damages and other observations**

Almost all of the pillow (more than 95%) was consumed by the fire. The mattress had a rectangular hole that measured approximately 800 mm (W) by 950 mm (L) where it had burnt completely. Altogether, almost 50% of the mattress was consumed. The fabric of the quilt was burnt in an small area that that faced the point of ignition, but was otherwise undamaged.

The surfaces of the long side wall had further damages as compared to the damages caused in Test 2, approximately 200 mm was burnt in the lengthwise direction. The surface coating on the short side wall had no additional damages. The ceiling panels had minor additional damages as compared to the damages caused in Test 2.

Half of the left hand side curtain was consumed. The curtain on the right hand side was undamaged (the damaged curtain from Test 3 was hanged in that position).

The mattress and the bedding material in the top bunk bed was undamaged, only a little sooty and wet from the water sprays. The surface layer on the underside of the bottom plate of the upper bunk bed had burnt approximately 300 mm in addition to the damage caused in Test 2.

No damage was recorded on the outside “hull”.

Furthermore, it was observed that no smoke spread to the adjacent cabin during the test but a small portion of the floor was wet by water from the nozzle in the corridor.

See Appendix B for temperature graphs.
Figure 23  Smoke escaping the window opening in Test 4a).

Figure 24  The fire damages in Test 4a). Almost the whole of the pillow and approximately 50% of the mattress was consumed by the fire. The damages to the surface coating on the bulkheads primarily originated from the previous tests.
6.5 Test 4b)

Date: 2007-12-05

The fifth fire test was conducted with the door to the cabin open. The window was closed and both cabin nozzles as well as the nozzles inside the corridor was disconnected.

The bottom bed on the left hand side was fitted with a foam type mattress, the other three bunk beds with spring mattresses.

**Fire test chronology**

-02:00 Start of measurements.
00:00 Fire ignition.
00:50 White smoke from the pillow, indicating that it is heated up.
01:05 The pillow ignites.
01:32 The first fire detector (ionisation type) activates.
02:20 The wood crib falls to the left.
02:40 The flames touch the underside of the upper bunk bed.
02:45 Approximately half of the pillow is burning.
03:30 It is observed that the fire primarily spreads towards the short side wall.
03:45 Most of the pillow has been consumed by the fire.
04:05 The curtain ignites and the fire spreads in the surface coating on the short side.
04:20 The fire spreads up the short side wall.
04:35 The whole exposed area of the mattress is on fire.
05:00 Large amount of dense, black smoke in the corridor is observed.
05:30 Flames out of the cabin and the corridor is observed.
06:00 The lower bunk bed on the right hand side and the table top is on fire.
09:00 Heavy flames out of the corridor opening.
09:33 The measurement system partially malfunctions due to computer crash.
10:30 The wood struts on the outside of the right hand long side walls ignites by flames from flames from gaps of the wall panels.
10:35 The cabin is completely black.
10:40 Cabin B starts to fill with grey smoke.
14:00 Still large flames from the open end of the corridor.
14:30 The wood frame around the window opening of Cabin A is burning and is manually extinguished.
18:55 Cabin B is completely filled with smoke.
20:30 The fire size is reduced, flames through the doorway is smaller and the fire size in the carpet of the corridor is reduced.
26:00 It is observed that the suitcases inside the cabins is on fire.
27:30 Smoke is streaming out from the gaps around the window of Cabin B.
42:20 The smoke in the corridor is cooled by means of manual water sprays.
44:10 The smoke inside Cabin B is cooled through an opening under the window, using a hand held nozzle, to reduce risk of explosion due to uncombusted gases.
46:00 The measurement system is stopped.
56:30 The measurement system is re-started.
155:50 The measurements are terminated.
**Damages and other observations**

**Cabin A**
All combustible material was consumed and the cabin was completely black inside.

The Pullman bunk beds had fallen from the walls.

All wall panels were intact, however, quite deformed. All C-clamps were in place.

Two ceiling panels had fallen to the floor, the second and third, as counted from the short side wall with the window opening. The first and fourth panels were severely deformed. It was observed that the fourth panel partly was held in place by the support column for the cabin thermocouples. The sixth and seventh panel, as counted from the short side wall, was partly deformed.

One light fixtures had fallen to the floor with the ceiling panel (the second panel). The other had fallen to the floor. It was, however, verified that the protection boxes on the outside of the ceiling panels remained in place and intact.

The ventilation unit had fallen to the floor, and probably contributed to the collapse of the third ceiling panel. The vertical supports for the unit remained in place and had separated at the joints between the panel and the supports.

The aluminium floor plates had melted over a large floor area and was completely consumed in the area between the bunk beds. The overall size of the damage was approximately 2 m². Additionally, the aluminium floor plates had melted in an area of approximately 0.2 m² in front and under the position of the table top and in two smaller spots close to the doorway opening.

The underlying fire insulation was damaged in a corresponding area.

After the removal of the aluminium floor plates and the underlying insulation, it could be concluded that the composite deck was blackened and burnt in a rectangular pattern that was approximately 2700 mm in length and 2100 mm wide (5.7 m²). The core was damaged in a pattern that was 1500 mm in length and 1300 mm in width (2 m²).

The fire insulation (Thermal Theramics FireMaster) at the ceiling was visually unaffected, except for a small area centrally in the cabin, where it seemed to be eroded. It was also observed that the exposed layer of the ceiling insulation had hardened in an area that corresponded to the inner footprint of Cabin A. A small wall insulation area directly above the window opening had also hardened, to a distance of about 200 mm below the ceiling. For all other surfaces, including the area on the opposite side of the beam, the insulation was still soft and undamaged.

The insulation may have shrunk a little, as visually noted at the joints between the outer layer of insulation.

See Appendix B for temperature graphs.

**Cabin B**
Cabin B had no combustible material except for the surface coating on the wall and ceiling panels. All surface coating had been consumed and the wall coating was consumed in an area extending approximately 600 – 700 mm from the ceiling.
The ceiling panels were slightly deformed and it is suspected that smoke from the void space spread to the cabin through the joints of the panels.

The rest of the cabin was sooty and the day after the test, it was observed that the steel lining around the window opening was rusty, probably by the formation of corrosive HCl.

**Corridor**
The wall panels were slightly deformed along the whole length of the cabin, however, all the C-clamps remained in place and intact.

The floor carpet was consumed, except for a small part, approximately 200 – 300 mm in length at the open end and a length of approximately 2400 mm at the closed end. The aluminium floor plate was deformed by the heat for the whole exposed length, but had not melted in any part.

The surface coating at the ceiling was completely consumed and the surface coating at the walls were consumed except that they were partly consumed at the inner part of the corridor, approximately 2400 mm from the end wall.

![The position of the large suitcases prior to the Test 4b)](image)

**Figure 25**  The position of the large suitcases prior to the Test 4b).
Figure 26  The position of the medium sized suitcases prior to Test 4b).

Figure 27  View of the from the small observation window at the long side cabin wall during Test 4b).
Figure 28  Dense, black smoke from the doorway opening, prior to flashover in Test 4b).

Figure 29  Flames through the doorway opening at or slightly after flashover in Test 4b).
Figure 30  Fire size after flashover in Test 4b). Some of the wall panels of Cabin A has separated.

Figure 31  Detail of the separation between the wall panels of Cabin A. The steel is very hot. Note that this side was not clamped as in end-use practice, since it faced the outside perimeter of the test.
Figure 32  Damages after Test 4b). The Pullman bunk beads at the left hand side had fallen to the floor.

Figure 33  Damages after in Test 4b). Two ceiling panels had fallen to the floor, the second and third, as counted from the short side wall with the window opening.
Figure 34  Another view of the collapsed and deformed ceiling panels of Cabin A.

Figure 35  The damages inside the corridor after Test 4b).
Figure 36  The fire insulation under the deck after Test 4b).

Figure 37  A close up of fire insulation under the deck after Test 4b).
Figure 38  The damages to the ceiling panels of the corridor after Test 4b).

Figure 39  The damages to the deck after Test 4b), after the cabins and the corridor had been dismantled.
6.6 Test 5a)

Date: 2007-12-07

Test with a heptane pool fire in the window of cabin B.

The drencher system was started moments after fire ignition and the intention was to determine if the drencher system could prevent fire spread on the outside surface of the superstructure.

Fire test chronology
- 02:00 Start of measurements.
  00:00 Fire ignition.
  00:15 Start of the drencher system.
  00:30 The flames reach to the inner side of the opening.
  01:30 The fire size is increasing.
  04:00 The fire size is still increasing.
  05:30 It is observed that the water coverage is poorer at the top, left hand side corner of the window opening.
  06:15 The fire size is still increasing. The flames out of the opening is approximately 1 m in height.
  09:30 The fire size is still increasing and the flames that stretch out of the opening is now approximately 1.5 m in height.
  11:00 The area above the window opening is ignited, but the fire is almost immediately extinguished by the water.
  13:40 The intensity of the fire is reduced.
  13:50 The intensity is rapidly reduced, indicating that the fuel is burning out.
  14:05 The fire is out as the fuel has been consumed.
  16:00 The water flow is stopped.
  19:00 The measurements are terminated.

Damages and other observations
The outside of the superstructure was burnt and blackened in narrow, almost rectangular patterns that extended approximately 200 mm from the top of the window opening. In other words, the fire damages were minimal.

See Appendix B for temperature graphs.
Figure 40  The maximum fire size, prior to the complete consumption of the heptane fuel. The water flowing down the vertical surface is clearly visible.

Figure 41  Fire damages above the window opening after the test.
6.7 Test 5b)

Date: 2007-12-07

Test with a heptane pool fire in the window of cabin B.

For this particular test, the fire was allowed to be established on the outside surface before the drencher system was started. The intention was to determine the fire suppression capability of the drencher system.

Fire test chronology
-02:00 Start of measurements.
00:00 Fire ignition.
00:18 Flames are extending out from the top of the window opening.
01:00 The flames touch the outer side and the surface start to become blackened.
03:04 The flames ignites the superstructure.
03:30 Flames extend to about 1.5 m above the top of the window opening.
04:10 Flames to the top of the test set-up.
04:30 The fire spreads vertically, along the small overhang at the top of the super-structure.
05:35 Start of the drencher system.
05:45 The fire is immediately suppressed.
06:00 The fire on the outside superstructure is completely extinguished.
06:45 Flames are extending our from the opening and the pool fire is burning at full intensity, however, the outer surface is not igniting.
09:00 The flames are approximately 1 m in height.
10:30 The water flow is stopped in order to investigate the re-development of the fire on the outside of the superstructure.
12:00 Flames are touching the surface but it is not ignited.
13:30 The flames reach to about half the height and the surface re-ignites.
14:00 The fire is intense.
17:00 The fire size is reduced, the heptane fire is decreasing.
17:30 The intensity is rapidly reduced, indicating that the heptane fuel is burning out.
17:48 The fire source is out as the heptane fuel has been consumed.
19:30 The drencher system is re-started.
19:45 The fire is completely extinguished.
33:00 The measurements are terminated.

Damages and other observations
After the first activation of the drencher system at 05:35 (min:sec), the superstructure was burnt in rectangular pattern that was approximately 600 mm in width that extended from the top of the window opening to the top of the structure.

As the fire was allowed to re-develop, additional damages were recorded after the test was terminated. The area that was burnt was slightly larger than the window opening itself, approximately 1100 mm and extended to the top of structure. By visual observations, it seemed that the outer laminate had burnt through, however, the core was not damaged.

See Appendix B for temperature graphs.
Figure 42  The fire size moments before the activation of the drencher system.

Figure 43  The fire size moments after the activation of the drencher system.
Figure 44  The fire damages after Test 5b).
7 Analysis of the test results

All measurement graphs from the tests are provided in Appendix B. Given below is an analysis of the results. The fire detection times are discussed in a separate sub-section.

7.1 Test 1

The water mist nozzle at the centre area of the cabin activated at 03:42 [min:sec] after ignition and this immediately reduced the gas temperatures inside the cabin. The maximum recorded gas temperature, as measured 100 mm below the ceiling (C21) was around 70°C. It should be noted that only one of the nozzles inside the cabin activated, the nozzle at the centre area of the cabin. Note that this nozzle had a lower nominal activation temperature (54°C) as compared to the nozzle above the window opening (93°C).

Due to the rapid activation of the nozzle the temperatures recorded in the surrounding superstructure was very low. The temperatures (C41 and C46) of the composite structure forming the deck did not increase at all. The ceiling surface temperatures, as measured on the outside face of the B-class ceiling of the cabin, (C42 and C47) peaked at 25°C, respectively.

The temperatures (C45 and C50) of the composite structure that formed the bottom deck peaked at 24°C and 23°C, respectively.

The minimum recorded oxygen concentration was 17.1 vol-%, the maximum recorded Carbon Monoxide concentration was 0.1 vol-% and the maximum recorded Carbon Dioxide concentration was 3.1 vol-%. The measured concentrations do not provide any acute risk for life.

The maximum recorded pressure inside the cabin was approximately 16 Pa. At the activation of the sprinkler system, the pressure rapidly dropped to -37 Pa, probably due to the cooling effect of the water droplets. However, soon after the pressure increased to normal atmospheric pressure.

7.2 Test 2

For the second test, the high-pressure water mist system was disconnected, however, both the cabin door and window remained closed throughout the test.

The gas temperature inside the cabin peaked at 173°C, just prior to the self-extinguishment of the fire. The surface temperatures measured at the surrounding structure did not reach any high levels. The temperatures (C41 and C46) of the composite structure forming the deck did not increase at all. The ceiling surface temperatures, as measured on the outside face of the B-class ceiling of the cabin, (C42 and C47) peaked at 45°C, respectively.

The gas temperatures, as measured in the ceiling void space between the cabin and the superstructure, (C43 and C48) peaked at about 38°C, respectively. This is an indication that very limited amounts of gas spread from the cabin and up to the ceiling void space.

The temperatures (C45 and C50) of the composite structure that formed the bottom deck peaked at 32°C and 27°C, respectively. A comparison of these two measurement points indicate that the shadow effect caused by the bunk beds had some influence on the tem-
perature. The measurements point that were positioned directly under the floor carpet (C44 an C49) followed the same trend and peaked at 42°C and 35°C, respectively.

Both the cabin pressure and the oxygen concentration measurements indicate that the fire was completely extinguished approximately 05:30 after ignition. This is the moment when both the oxygen concentration and the pressure starts to increase.

The minimum recorded oxygen concentration was 10.6 vol-%, the maximum recorded Carbon Monoxide concentration was 0.7 vol-% and the maximum recorded Carbon Dioxide concentration was 7.8 vol-%. The measured concentrations are acute lethal.

The pressure inside the cabin grew to approximately 60 Pa, however, when the fire started to become reduced, the pressure reduced and was approximately -20 Pa when the fire was out.

7.3 Test 3

The third fire test was conducted with the door to the cabin open. The window was closed and the high-pressure water mist system was fully functional.

Both water mist nozzles inside the cabin activated more or less simultaneously approximately 03:00 after ignition. The gas temperatures inside the cabin was immediately reduced and maximum recorded gas temperature, as measured 100 mm below the ceiling (C21) was around 76°C. It should be noted that the corridor nozzle closest to the doorway opening activated a few seconds after the nozzles inside the cabin.

Due to the rapid activation of the water mist nozzles the temperatures recorded in the surrounding structure was very low. The temperatures (C41 and C46) of the composite structure forming the deck did not increase at all. The ceiling surface temperatures, as measured on the outside face of the B-class ceiling of the cabin, (C42 and C47) peaked at about 24°C, respectively.

The temperatures (C45 and C50) of the composite structure that formed the bottom deck peaked at 22°C and 21°C, respectively.

The minimum recorded Oxygen concentration was 19.0 vol-%, the maximum recorded Carbon Monoxide concentration was 0.05 vol-% and the maximum recorded Carbon Dioxide concentration was 1.5 vol-%. The measured concentrations does not provide any risk for life. It can be observed that the minimum oxygen concentration was higher and the maximum Carbon Monoxide and Carbon Dioxide concentrations, respectively, were lower as compared to Test 1, where the door was closed.

The cabin pressure did not fluctuate much as the door was open.

7.4 Test 4a)

The fourth fire test was conducted with the door and the window to the cabin open. The high-pressure water mist system was fully functional, except that the nozzle above the window opening was disconnected. The reason for disconnecting this particular nozzle was to challenge the system and investigate whether one cabin nozzle could prevent fire spread through the open window opening.

The nozzle activated 02:35 after ignition, which reduced the maximum recorded gas temperature, as measured 100 mm below the ceiling (C21) to around 83°C. The
temperature drop was, however, not as rapid as in Tests 1 and 3, simply because the fire was not suppressed as quickly, probably due to the higher degree of natural ventilation to the fire. Despite this, none of the nozzles in the corridor activated.

Although the fire was a little larger compared to the previous tests, the temperatures (C41 and C46) of the composite structure forming the deck did not increase at all. The ceiling surface temperatures, as measured on the outside face of the B-class ceiling of the cabin, (C42 and C47) peaked at about 30°C, respectively.

The temperatures (C45 and C50) of the composite structure that formed the bottom deck peaked at 25°C and 24°C, respectively.

The minimum recorded Oxygen concentration was 18.5 vol-%, the maximum recorded Carbon Monoxide concentration was 0.05 vol-% and the maximum recorded Carbon Dioxide concentration was 2.0 vol-%. The measured concentrations does not provide any risk for life. Also for this test, it was observed that the minimum oxygen concentration was higher and the maximum Carbon Monoxide and Carbon Dioxide concentrations, respectively, were lower as compared to Test 1, where the door was closed. The values were comparable to Test 3.

7.5 Test 4b)
7.5.1 General test results
The fifth fire test was conducted with the door to the cabin open. The window was closed and both the water mist nozzles inside the cabin as well as the nozzles inside the corridor was disconnected. This allowed the fire to develop to a very intense flashover. Unfortunately, the measurement system partially malfunctioned at 09:33 and was not possible to re-start until 56:30. Therefore, some measurement data was lost.

The system crash problem affected almost all temperature measurements, however, the heat release rate measurements were not affected and due to the time delay associated with the move of the heat wave, the peak heat temperatures in the superstructure could be determined when the measurement system was re-started. The measurements associated with the gas temperatures of the thermocouple tree inside Cabin B and in the corridor malfunctioned at 46:00 but was restarted at 56:30.

The total heat release exceeded 1.5 MW for a period of over twelve minutes. In reality, the fire size was larger, but smoke escaped the hood of the calorimeter and the fire size was therefore underestimated.

The ceiling surface temperatures, as measured on the outside face of the B-class ceiling of the cabin, (C42 and C47) peaked at 251°C at and 285°C, respectively, at the moment of the measurement system malfunctioned, i.e. at 09:33 [min:sec]. The temperatures were most likely higher at the time the cabin structure collapsed, but the these temperatures were not possible to determine.

The Plate Thermometer (C39) positioned at the floor of Cabin A peaked at 813°C just prior to the malfunction of the measurement system. This corresponds to a heat radiation flux of approximately 80 kW/m². The Plate Thermometer (C40) positioned at the floor of the corridor peaked at 103°C, which corresponds to approximately 3 kW/m². After the re-start of the measurement system, none of these measurement channels showed any reliable readings due to the deformation and long exposure to severe heat.
The minimum recorded Oxygen concentration in the cabin reached 0.0 vol-% at 06:45 [min:sec]. This indicates that the measurement point, that was positioned 500 mm below the ceiling, was totally engulfed in flames at that time. The maximum recorded Carbon Monoxide concentration was around 5 vol-% just prior to the malfunction of the measurement system. The maximum recorded Carbon Dioxide concentration was 17.3 vol-% just prior to the malfunction of the measurement system. No reliable gas concentration data was determined after the re-start of the measurement system.

From the visual observations and the temperatures measurements inside Cabin B it seems that hot combustion gases started to fill the this cabin after approximately 10:40 [min:s] after fire ignition. At 18:30 a rapid increase of the gas temperatures inside the cabin is recorded. This may be an indication of when a larger gap between the ceiling panels opened up. Higher gas temperatures, in the order of 270°C, was recorded inside Cabin B after approximately 40 minutes, which could be an indication that fire had spread from cabin to cabin. Moments later the measurement system malfunctioned and the peak gas temperatures inside Cabin B could not be determined.

The fire involved all combustible interior materials and floor covering of Cabin A and the corridor. Afterwards it was observed that all cabin panels were more or less deformed and two ceiling panels had fallen to the floor. The aluminium floor plates at the floor of the cabin had melted over a large area and were completely consumed in an area between the bunk beds. The underlying fire insulation and part of the composite deck were also damaged.

In the adjacent cabin (“Cabin B”) no combustible material was installed except for the surface foil coating on the wall and ceiling panels and the floor carpet. All surface coating in the ceiling had been consumed and the wall coating was burnt in the upper part of the cabin. The ceiling panels were slightly deformed and it is assumed that smoke from the void space spread to the cabin through the joints of the panels. The floor carpet was undamaged.

In the corridor, the wall panels were slightly deformed and the surface coating at the ceiling and walls were largely consumed by the fire. Much of the floor carpet was burnt and the aluminium floor plates were deformed but had not melted.

### 7.5.2 Test 4b Heat Release Rate (HRR)

Smoke gases escaping from the corridor opening were collected in a hood as described in section 3.1. The resulting heat release rate is plotted in Figure 45. After flashover the flow of hot gases was so high that part of the smoke plume hit the perimeter of the hood skirt and escaped into the test hall. This means that the measured HRR is underestimated but it is very difficult to estimate how large part of the flow that escaped. An approximate check can be made by comparing the total heat release rate with the available energy in the combustible materials in the cabin, see section 2.9.9 where the theoretical fire load is calculated to 3.1 GJ. Integration of the HRR curve results in a measured effect of 3.0 GJ, which indicates that the losses should have been limited.
The fire insulation under the upper deck and on the bulkheads was almost unaffected, except for a small spot approximately centred under Cabin A, where it seemed to be eroded. It was also observed that the exposed layer of the insulation had hardened in an area that corresponded to the inner base area of Cabin A, which indicates very high temperatures.

The temperatures (C41 and C46) of the composite structure forming the deck above Cabin A peaked at 142°C after approximately 85 minutes and at 127°C after approximately 97 minutes. No temperature increase had been measured at the time the measurement system malfunctioned, i.e. up until 09:33 [min:s]. Note that only two thermocouples were installed in the part of the superstructure that surrounded Cabin A.

For the part of the superstructure that surrounded Cabin B, several thermocouples (C101 to C120) were imbedded in the superstructure, both in the wall in the front of the cabin, in the side wall next to the cabin and in the ceiling deck above it. The table below shows the peak temperatures that were recorded.
Table 9  Peak temperatures recorded in the part of the superstructure that surrounded Cabin B.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Position</th>
<th>Peak temperature [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front wall</td>
<td>Top level</td>
<td>74</td>
</tr>
<tr>
<td>101</td>
<td>Top level</td>
<td>79</td>
</tr>
<tr>
<td>102</td>
<td>Top level</td>
<td>69</td>
</tr>
<tr>
<td>103</td>
<td>Mid-height</td>
<td>42</td>
</tr>
<tr>
<td>104</td>
<td>Mid-height</td>
<td>42</td>
</tr>
<tr>
<td>Side wall</td>
<td>Top level</td>
<td>78</td>
</tr>
<tr>
<td>106</td>
<td>Top level</td>
<td>78</td>
</tr>
<tr>
<td>107</td>
<td>Top level</td>
<td>60</td>
</tr>
<tr>
<td>108</td>
<td>Mid-height</td>
<td>45</td>
</tr>
<tr>
<td>109</td>
<td>Mid-height</td>
<td>47</td>
</tr>
<tr>
<td>110</td>
<td>Mid-height</td>
<td>42</td>
</tr>
<tr>
<td>Ceiling deck</td>
<td>Close to front wall</td>
<td>73</td>
</tr>
<tr>
<td>112</td>
<td>Close to front wall</td>
<td>65</td>
</tr>
<tr>
<td>113</td>
<td>Close to front wall</td>
<td>60</td>
</tr>
<tr>
<td>114</td>
<td>Mid-level</td>
<td>98</td>
</tr>
<tr>
<td>115</td>
<td>Mid-level</td>
<td>89</td>
</tr>
<tr>
<td>116</td>
<td>Mid-level</td>
<td>76</td>
</tr>
<tr>
<td>117</td>
<td>Close to corridor</td>
<td>114</td>
</tr>
<tr>
<td>118</td>
<td>Close to corridor</td>
<td>95</td>
</tr>
<tr>
<td>119</td>
<td>Close to corridor</td>
<td>89</td>
</tr>
<tr>
<td>120</td>
<td>Close to corridor</td>
<td>89</td>
</tr>
</tbody>
</table>

From these measurements it can be concluded that the lower deck temperatures were recorded in the area above Cabin B as compared to the area above Cabin A (C41 and C46). These seems logic as the area not was directly subjected to the fire. Similar temperatures were recorded in the front and side wall, respectively. It is also noticeable that significantly lower temperatures were recorded in at mid-height of the walls as compared to the top part.

The peak temperatures (C45 and C50) of the composite structure that formed the bottom deck could not be determined. Both thermocouples were destroyed by the fire and no reliable data was determinable at the time the measurement system was re-started. At the time the measurement system malfunctioned, i.e. about 4 minutes into the flashover, the temperature in these measurement points was less than 30°C.

7.5.4  Test results from the FTIR measurements

The results from the measurement with FTIR are presented in Table 9. Time resolved concentrations are shown in graphs of Appendix B, Figure 78 - Figure 82. Sampling was made in the upper part of the corridor opening which means that it represents the average concentration in the hot smoke gas layer flowing from the corridor. Concentrations in the cabin can be a bit higher, which can be seen from the cabin measurements, since some dilution is taking place in the corridor. The measurements were interrupted after 9.5 min, i.e. approximately 4 minutes into the flashover phase. However, the concentrations curves of CO and CO₂ levels out at a high level which indicates that maximum concentrations are reached within this period.

The concentration of HCl peaks just after flashover and then declines slowly, this is probably because all interior PVC foil was consumed in a short time following flashover
and the floor carpet started to burn soon after flashover. Although the wall foil is very thin the total amount in the cabin is almost 9 kg, and the floor represents 38 kg of PVC carpet, see Table 3. The measured maximum at 5 minutes is almost 20 000 ppm or 2% which means immediate incapacitation if inhaled.

HCN and NO concentrations were recorded but the spectral interference was too large to make certain interpretations of the spectra after 5 minutes. Both HCN and NO reach above 100 ppm within 5 minutes which is close to the limit for incapacitation. Maxima is certainly significantly higher and data indicates that HCN might have reached levels above 3000 ppm.

In a real situation the smoke gases would spread quickly to the surrounding parts in the main vertical zone. The flow of hot gases out from the cabin was measured with a bi-directional probe in the top door opening to about 2.5 m/s at the developed stage of the fire, i.e. after flashover. This cannot be directly translated to volume flow but a good estimate can be done using the zone model BRANZFIRE [7] with the measured heat release rate as source term. This gives a result of approximately 3 m³/s production of smoke gases in the developed stage. The results of this smoke production in an enclosed accommodation area are very severe. Considering CO as an example, assuming an average CO concentration of 3% during a 15 minutes developed stage would mean a total release of 27 m³ CO, which potentially can make a volume of 4500 m³ inescapable (0.6% CO), representing a ship accommodation space of more than 2100 m².

Table 10 below summarises the max concentrations measured and the averages between ignition and 9.5 minutes. The levels for incapacitation represent very severe conditions in which humans are incapacitated within 5 minutes, without safety factors. In a safety engineering process values should be chosen to give a larger margin, typically a safety factor in the order of 3.

Table 10  Results from FTIR measurements at the corridor exit.

| Compound                | Max concentration | Average concentration | Level for Incapacitation
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide, CO₂</td>
<td>12.5%</td>
<td>5.8%</td>
<td></td>
</tr>
<tr>
<td>Carbon monoxide, CO</td>
<td>3.36%</td>
<td>1.27%</td>
<td>0.6 - 0.8%</td>
</tr>
<tr>
<td>Hydrogen chloride, HCl</td>
<td>18800 ppm**</td>
<td>6600 ppm**</td>
<td>300 ppm</td>
</tr>
<tr>
<td>Hydrogen fluoride, HF</td>
<td>&lt; 5 ppm</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Hydrogen bromide, HBr</td>
<td>&lt; 10 ppm</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Hydrogen cyanide, HCN</td>
<td>&gt; 150 ppm*</td>
<td>-</td>
<td>150-200 ppm</td>
</tr>
<tr>
<td>Ammonia, NH₃</td>
<td>&lt; 5 ppm</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Nitrogen oxide, NO</td>
<td>&gt; 85 ppm*</td>
<td>-</td>
<td>100 ppm</td>
</tr>
<tr>
<td>Nitrogen dioxide, NO₂</td>
<td>*</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Sulphur dioxide, SO₂</td>
<td>&lt; 10 ppm</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

* ) Quantified during the first few minutes only due to strong spectral interference later in the experiment. See respective measurement graphs with time resolved concentrations.

**) The calibration range for HCl was 0 – 5100 ppm.
7.6  Test 5a)

For this test, the drencher system was started moments after fire ignition and the intention was to determine if the drencher system could prevent fire spread on the outside surface of the superstructure.

Visually, the fire gradually developed during the test and peaked at approximately 750 kW, approximately 12 minutes after ignition. The gradual growth of the fire can be explained by the heat up of the heptane fuel. When the fuel and the rims of the fire tray gets hotter the mass loss of the fuel increases. Some degree of combustion gases (smoke) was not collected by the Industry Calorimeter, indicating that the fire size was slightly larger than measured.

The temperatures measured at the surface of the superstructure (C51 and C52), reached to about 100°C and 45°C, respectively. The embedded thermocouple (C21) peaked at 26°C.

7.7  Test 5b)

For this test, the drencher system was activated when the fire was fully established on the outside of the superstructure.

The Heat Release Rate reached over 800 kW when the system was activated and the fire on the outside of the superstructure was immediately suppressed.

The temperatures measured at the surface of the superstructure (C51 and C52), reached to about 530°C and 740°C, respectively at the time the drencher system was activated. The fact that the temperature at position closer to the top of the opening was lower can be explained by the fact that it was slightly wet from the previous test. This is indicated by the fact the temperature reading levels out at 100°C for a couple of minutes. Both temperature readings were immediately reduced upon the activation of the system.

The imbedded thermocouple (C21) peaked at about 150°C at the activation, but was knocked down upon the activation of the system.
7.8 Analysis of the fire detection times

Different fire detection techniques and fire detectors were used in the tests. Table 11 gives the detection times of the detectors.

Table 11 Detector activation times in Cabin A.

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Detector</th>
<th>Activation time (mins:s)</th>
<th>Type of detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>01:28 [N/A]</td>
<td>Heat and smoke (ionisation)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>02:17 [02:40]</td>
<td>Combined heat and smoke (optical) detector</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>01:52</td>
<td>Smoke (dual optical) detector</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>02:22 [02:39]</td>
<td>As per no. 2, with a recessed installation plate</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>03:10</td>
<td>Sampling type detector</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>01:15 [N/A]</td>
<td>Heat and smoke (ionisation)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>02:15 [02:34]</td>
<td>Combined heat and smoke (optical) detector</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>02:15</td>
<td>Smoke (dual optical) detector</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>02:23 [02:28]</td>
<td>As per no. 2, with a recessed installation plate</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>02:50</td>
<td>Sampling type detector</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>01:20 [N/A]</td>
<td>Heat and smoke (ionisation)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>01:54 [02:24]</td>
<td>Combined heat and smoke (optical) detector</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>01:59</td>
<td>Smoke (dual optical) detector</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>01:56 [02:18]</td>
<td>As per no. 2, with a recessed installation plate</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>No indication</td>
<td>Sampling type detector</td>
</tr>
</tbody>
</table>

4a) 1 01:14 [N/A] Heat and smoke (ionisation)  
2 01:45 [02:05] Combined heat and smoke (optical) detector  
3 01:45 Smoke (dual optical) detector  
4 01:40 [02:05] As per no. 2, with a recessed installation plate  
5 01:56 Sampling type detector  
4b) 1 01:32 [N/A] Heat and smoke (ionisation)  
2 02:30 [02:40] Combined heat and smoke (optical) detector  
3 02:30 Smoke (dual optical) detector  
4 02:31 [02:40] As per no. 2, with a recessed installation plate  
5 02:43 Sampling type detector

Notes:

1) The fire detection time for a sampling type detector is generally influenced by the length of the sampling pipe and the air flow rate. In this particular case, the length of the pipe was 7 m.

2) The activation time of the heat response element within the particular detector, where applicable, is given within [square brackets]. The activation time of the heat response element of detector type 1 was not possible to determine due to design with one alarm output channel, which is indicated by N/A.
8 Conclusions

8.1 The fire integrity of the cabins and the corridor

Two tests challenged the fire integrity of the cabins and the corridor, i.e. when the high-pressure water mist system was disconnected. Test 2 where the cabin was sealed closed and Test 4b) where the doorway to Cabin A was open during the entire fire test.

No significant gas or construction temperatures were measured when the cabin door and window was closed. Visually, were little smoke spread from the cabin to the corridor. Furthermore, the gas temperatures, as measured in the ceiling void space between the cabin and the superstructure, indicate that very limited amounts of gas spread from the cabin. However, acute lethal gas concentration inside the cabin were recorded. The fire damage inside the cabin was limited and primarily concentrated to the lower bunk bed and the nearby surface coating, but the walls and the ceiling was black from soot.

During Test 4b), the fire involved all combustible interior materials and the floor covering inside the cabin. Most of the floor covering in the corridor was also consumed. After the fire, it could be concluded that most of the cabin wall panels were deformed and two of the ceiling panels had fallen to the floor. The cabin aluminium floor plates had melted over a large area and were completely consumed in the area between the bunk beds. The underlying floating floor insulation and part of the composite deck were also severely damaged in a limited area.

The construction of the cabins and the corridor had a B-15 fire rating, however, as the measurement system malfunctioned at 09:33 [min:sec] it was not possible to determine when the integrity of the Cabin A was lost.

The fire spread from Cabin A to Cabin B, indicated by gas temperatures in the order of 270°C inside Cabin B took approximately 40 minutes. This correlates well with the fact that each of the cabin ceilings had a B-15 fire rating.

8.2 The fire integrity of the superstructure

The FireMaster® fire insulation under the upper deck and on the bulkheads was visually almost unaffected except for a small spot centred approximately below the cabin, where the insulation seemed to be eroded. It was also observed that the exposed surface of the insulation had hardened in an area that corresponded to the inner footprint of Cabin A.

With regard to the fire integrity of the composite construction it can be concluded that, although the flashover had long duration and high intensity, the maximum temperature obtained in the core of the deck just above the cabin reached to about 140°C after about 90 minutes. This was enough for a de-lamination to occur but the limited area involved would probably quite easily have been repaired after the fire.

Temperatures measured at inside the structure of the top deck reached to levels associated with standard furnace tests. However, it was shown that the temperature exposure varied a lot with the distance from the fire.

The fire protection given by the floating floor was insufficient, which led to severe damages to the composite deck below. The aluminium plates that that were laid on top of the 20 mm Rockwool® layer of fire insulation had partly melted, which means that the temperatures of the floor reached at least 660°C and the radiation levels were shown to be in the order of 80 kW/m².
8.3 The performance of the high-pressure water mist system

When the high-pressure water mist system was fully or partially (one cabin nozzle disconnected in Test 4a) functional no significant gas temperatures inside the cabin or corridor were recorded. Due to this, no significant temperatures were recorded on the outside of the ceiling panels, under the fire insulation on the floor or at the inside of the superstructure.

Furthermore, no lethal gas concentrations inside the cabin were recorded when the sprinkler system was fully or partially functional.

Acute lethal gas concentrations inside the cabin were recorded when the sprinkler system was out of function, both during Test 2, when the closed door prevented full flashover and during the flashover experienced in Test 4b) when the door was open.

8.4 The efficiency of the outside drencher system

The drencher system prevented fire spread on the outside of the superstructure and suppressed a fire established on the outer surface. When activated after the fire had established on the surface, the fire was suppressed almost instantaneously.

The water application rate was fairly low, 2.5 L/min per m² of the vertical surface. It could be argued that the water application rate in practice should be higher for example due to the effect from external wind. However, the spray pattern from the nozzles used in these tests is probably relatively insensitive to wind conditions but this should be further investigated experimentally.

8.5 The performance of the fire detection system

The optical smoke detector was generally 30 to 60 seconds faster as compared to the heat detectors. This is logical as all fire scenarios was ignited such that the pillow (generated black smoke) primarily was involved. An important conclusion is that there is no significant difference between the performance of the detector with the recessed installation as compared to a traditional installation.

The fire integrity of the recessed steel plate and the 25 mm thick Rockwool® fire insulation on the opposite side of the ceiling panel of the cabin proved, at least visually, to work properly. The steel plate was intact and the insulation was in place after the flashover fire experienced in Test 4b). As a comparison, it was noted that the light fixtures (made from aluminium) were severely damaged, although the protecting insulation boxes mounted above the holes prevented fire spread.

8.6 Suggested improvements of the fire safety requirements in SOLAS

Based on the tests it can be concluded that it is possible to obtain a high degree of fire safety using a combustible composite construction. However, the tests reveal some week points of the current fire safety requirements of SOLAS:
Today’s wall and ceiling surface linings consist of very thin, in the order of 50 to 150 µm, coatings. These coatings meet high standards for interior finishes, exhibiting good appearance (many different colours and printed patterns, are available), scratch resistance, reparability, etc. The film is bonded at high temperature to the top surface of the sheet steel. These coatings have good fire characteristics, well exceeding the present regulatory requirements due to the limited amount of combustibles. However, concerns about the toxicity of PVC, as verified by these fire tests, have prompted the development of several PVC-free alternatives from different manufacturers. These coatings are typically made from HMP or PET film. It is suggested that PVC-free coatings should be required in the SOLAS requirements.

The floor carpet used in the tests fulfils present SOLAS requirements. Still, it is clear that the carpet contributed a lot to the size of the fire. It did also contain PVC.

For a passenger or crew cabin the mattress and the bedding components constitute large part of the fire load inside the cabin. It is therefore important that these components have as high resistance to ignition and flame spread as possible. These fire tests indicate that compliance with the present regulatory requirements is not a guarantee that mattresses will not burn severely when ignited with a larger fire ignition source.

SOLAS Chapter II-2, regulation 10 allow that spaces having little or no fire risk, such as voids, public toilets, carbon dioxide rooms and similar spaces not to be fitted with sprinklers. However, these fire tests shows that automatic nozzles inside the ceiling void space could have limited the fire exposure to the ceiling deck and prevented fire spread between the cabins.
9 References

1 “60 minute Load-Bearing Composite Bulkhead, GRE/PVC Sandwich Panel Type”, Thermal Ceramics FireMaster Data Sheet FM 4.73, Rev 0, dated August 2006

2 “60 minute Load-Bearing Composite Deck, GRE/PVC Sandwich Panel Type”, Thermal Ceramics FireMaster Data Sheet FM 4.72, Rev 0, dated August 2006

3 Tewarson, SFPE Handbook of Fire Protection Engineering

4 “Model WSTM – 5.6 K-factor Specific Application Window Sprinklers, Horizontal and Pendent Vertical Sidewall”, TFP620, TYCO Fire & Building Products, July, 2005


6 Nyman, Hans, ”Fartygsventilation och brandskydd, Brandforsk projekt 402-051”, Brandskyddslaget rapport 100261 (in Swedish)


Cabins and corridor
With the position of sprinklers and T/C's
Superstructure
With the position of the thermocouples

Dimensions:
- Bottom deck: 6534 mm (L) x 6054 mm (W)
- Top deck: 6534 mm (L) x 6002 mm (W)
- Front wall: 6534 mm (W) x 4200 mm (H)
- Side wall: 6002 mm (L) x 2650 mm (H)
Position of thermocouples

Detailed drawing for T/C's:
C41-C45, C46-C50, C81-C85 and C86-C90

Outside
Composite panel (top deck)
FireMaster insulation
Surface temp. (outside)
Gas temp.
B-class panel
Void space
Surface temp.
Cabin
Al. plate
Rakwool Fire insulation
Composite panel (bottom deck)
Concrete floor
Surface temp. (under floor carpet)
Plate Thermometer
Surface temp. (under insulation)
Bulkeads
Cabin and superstructure
Fire insulation and steel lining around window opening

Steel lining around window opening

Rockwool fire insulation

1.5 mm steel

B-class panel

Void space

FireMaster insulation

Composite panel

Cabin

Outside

50  200  100  52
Window opening of Cabin B
Position of fire tray and thermocouples

Front view

Side view

C21 (un-exposed side)
C22, Plate Thermometer (only used in Test 3b)

2 mm steel plate
20 mm insulation
20 mm insulation
Table top

C75/C94
C76/C95
C77
C78
Appendix B: Measurements graphs

Figure 46   Gas temperatures at the thermocouple tree inside Cabin A in Test 1.

Figure 47   The cabin pressure in Test 1.
Figure 48  The oxygen concentration (O$_2$) in Test 1.

Figure 49  The Carbon Monoxide (CO) and Carbon Dioxide (CO$_2$) levels in Test 1.
Figure 50  Gas temperatures at the thermocouple tree inside Cabin A in Test 2.

Figure 51  The cabin pressure in Test 2.
Figure 52  The oxygen concentration (O₂) in Test 2.

Figure 53  The Carbon Monoxide (CO) and Carbon Dioxide (CO₂) levels in Test 2.
Figure 54  Gas temperatures at the thermocouple tree inside Cabin A in Test 3.

Figure 55  Gas temperatures at the thermocouple tree inside the corridor in Test 3.
Figure 56  The cabin pressure in Test 3.

Figure 57  The oxygen concentration (O₂) in Test 3.
Figure 58  The Carbon Monoxide (CO) and Carbon Dioxide (CO₂) levels in Test 3.

Figure 59  Gas temperatures at the thermocouple tree inside Cabin A in Test 4a).
Figure 60  Gas temperatures at the thermocouple tree inside the corridor in Test 4a).

Figure 61  The cabin pressure in Test 4a).
Figure 62  The oxygen concentration ($O_2$) in Test 4a).

Figure 63  The Carbon Monoxide (CO) and Carbon Dioxide (CO$_2$) levels in Test 4a).
Figure 64  Total Heat Release Rate from the fire in Test 4b).

Figure 65  The gas temperatures at the thermocouple tree in Cabin A in Test 4b).
Figure 66  The gas temperatures at the position of the water mist nozzles (disconnected) inside Cabin A in Test 4b).

Figure 67  The temperatures at the Plate Thermometers at the floor in Test 4b).
Figure 68  Measured plate thermometer surface temperature for different heat radiation levels, to be compared with plate thermometer temperatures in Figure 67.

Figure 69  The oxygen concentration (O₂) in Test 4b.
Figure 70  The Carbon Monoxide (CO) and Carbon Dioxide (CO₂) levels in Test 4b).

Figure 71  The gas temperatures at the thermocouple tree in corridor outside Cabin A in Test 4b).
Figure 72  The gas temperatures at the thermocouple tree in Cabin B in Test 4b).

Figure 73  The gas temperatures at the thermocouple tree in corridor outside Cabin B in Test 4b).
Figure 74  The temperature inside the composite deck above Cabin A in Test 4b).

Figure 75  The temperature in the front wall in front of Cabin B in Test 4b).
Figure 76  The temperature in the side wall next to Cabin B in Test 4b).

Figure 77  The temperature in ceiling deck above Cabin B in Test 4b).
Figure 78 Concentration of CO$_2$ from FTIR measurement at the corridor opening in Test 4b).

Figure 79 Concentration of CO from FTIR measurement at the corridor opening in Test 4b).
Figure 80  Concentration of HCl from FTIR measurement at the corridor opening in Test 4b).

Figure 81  Concentration of HCN from FTIR measurement at the corridor opening in Test 4b).
Figure 82 Concentration of NO from FTIR measurement at the corridor opening in Test 4b).
Appendix C: Selected photos from the tests and the construction process

Photo 1. The panels were glued and laminated together.

Photo 2. A wooden structure was built to support the upper bulkhead along two sides.

Photo 3. Mounting of the A-60 insulation, four layers of blanket with aluminium foil in between the layers.

Photo 4. The four layers of insulation on the upper deck at the stiffener.

Photo 5. The complete insulated structure.

Photo 6. Detail of the fire insulation.
Photo 7. The start of the construction of the cabins and the corridor.

Photo 8. The construction of the cabins and the corridor. The void space was later sealed on the two open sides.

Photo 9. Detail of the void between the cabins walls and the fire insulation.

Photo 10. The fire insulation around the window openings.

Photo 11. The void space between the ceiling of the cabins and the corridor and the surrounding superstructure, with the ventilation system.

Photo 12. Detail of the ‘boxes’ of insulation that covered the light fixtures.
Photo 13. The steel frame around the window openings (seen from the outside).

Photo 14. The pipe connection to one of the water mist nozzles.

Photo 15. One of the water mist nozzles inside the cabin.

Photo 16. One of the lighting fixtures in the corridor.

Photo 17. The hat rack inside cabin A.

Photo 18. The Pullman bunk beds inside the cabin.
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