Preliminary analysis report - Eco-Island ferry

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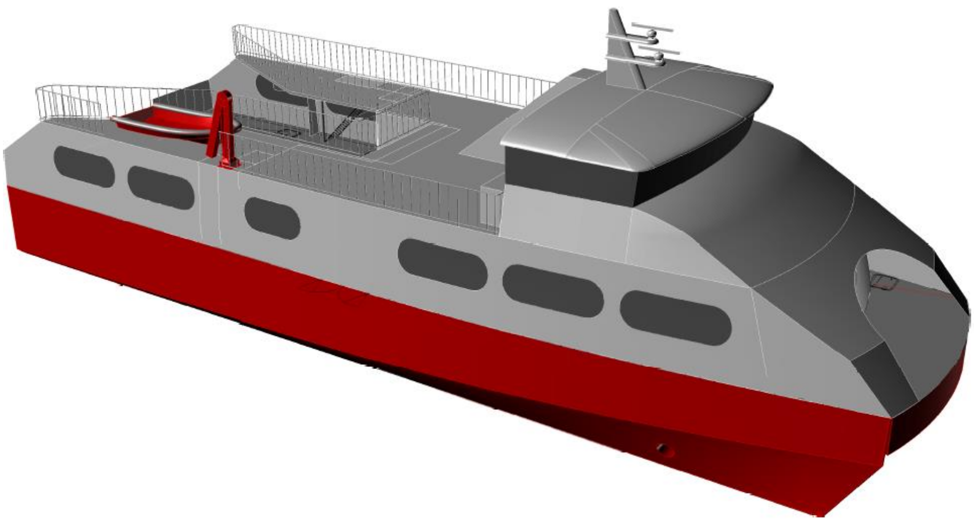
SP Technical Research Institute of Sweden



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SP Fire Research
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Abstract

This report contains the preliminary analysis in qualitative terms for the Eco-Island ferry. The base design of the Eco-Island ferry is a ship with structures in carbon fibre reinforced polymer composite instead of steel. The engine room is fitted with thermal insulation and spaces for passengers have surfaces of low-flame spread characteristics. A number of prescriptive and functional fire safety requirements are challenged by the base design, Primarily exterior surfaces are combustible and unprotected, which could provide initial fuel, secondary fuel and extension potentials to a fire. Furthermore, many divisions internally have combustible material behind the surface of low flame-spread characteristics, which may affect fire growth as well as smoke generation and toxicity. Based on a hazard identification workshop carried out by a design team, seven different groups of spaces were identified with similar conditions for fire scenarios. Throughout the processes, several suitable risk control measures were identified. Instead of firmly defining what combinations of these to be further evaluated in the quantitative analysis, it was suggested that all possible combinations could form risk control options. Applied to the base design, the risk control options form the trial alternative designs to be evaluated through the design fire scenarios. Yet, a number of risk control measures likely to be implemented were listed and potential risk control measures defined.

Key words: regulation 17, FRP composite, alternative design, fire safety.

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Summary

This report contains the preliminary analysis in qualitative terms, as described by Circular 1002 (MSC/Cric.1002 [6]), for the Eco-Island ferry.

The base design of the Eco-Island ferry is designed with structures in carbon fibre reinforced polymer composite instead of steel. The engine room is fitted with thermal insulation and spaces where people may be on a normal basis have surfaces of low-flame spread characteristics. Doors where A-class requirements apply are made in A-0 standard. The ship fulfils applicable prescriptive requirements regarding the fire safety organization, fire fighting routines, active fire protection systems and equipment.

The prescriptive requirements challenged by the base design primarily concern:

- sufficient thermal insulation is not provided in several places which may allow fire to spread to adjacent spaces.
- structures are not made in non-combustible material and may be deteriorated by fire and collapse;
- escape routes on ro-ro deck are not thermally protected from fire on the decks below;
- ro-ro deck is not protected from fire in the accommodation space or engine room;
- accommodation space is not protected from fire on ro-ro deck; and
- surfaces in auxiliary machinery spaces do not achieve low flame-spread characteristics.

Furthermore, the following significant effects on fire safety are considered:

- exterior surfaces are combustible and unprotected which could provide initial fuel, secondary fuel and extension potentials to a fire;
- many divisions internally have combustible material behind the surface of low flame-spread characteristics, which may affect fire growth as well as smoke generation and toxicity;
- the engine room bottoms are only protected with a surface of low flame spread characteristics;
- alternative evacuation stations are not provided; and
- fire containment is improved in the engine room on account to improved thermal insulation.

Based on a hazard identification workshop carried out by a designated design team, seven different groups of spaces were identified with similar conditions for fire scenarios:

1. Accommodation space
2. Engine rooms
3. Auxiliary machinery spaces
4. Void spaces
5. Wheelhouse
6. Ro-ro deck
7. Stairways

Throughout the processes of the Regulation 17 assessment, several suitable risk control measures were identified. Instead of firmly defining what combinations of these to be further evaluated in the quantitative analysis, it was suggested that all possible combinations could form risk control options. Applied to the base design, the risk control options form the trial alternative designs to be evaluated through the design fire scenarios. Yet, a number of risk control measures likely to be implemented were listed and potential risk control measures defined.

1 Background

The background of this report is given subsequently, commencing with an introduction to the research project "Øko-Ø-færge" (Danish for Eco-Island ferry), the ship with the same name and the objective to evaluate alternative fire safety design and arrangements. Subsequently follow brief descriptions of the applicable regulations for alternative fire safety design and arrangements as well as of the analysis procedure when making claim to these regulations. The design team responsible for the fire safety assessment of the alternative design and arrangements is thereafter presented.

1.1 The Eco-Island ferry project

It was after a kick off meeting in the EU project MARKIS in 2010 with the headline "Light Weight Marine structures" that an industrial group in North Jutland, Denmark and SP Technical Research Institute of Sweden started to discuss displacement ferries with reduced environmental footprint. This led to a Swedish-Danish consortium with the objective to open up for the construction of this type of ferry in the Swedish and Danish region. The project was given the name "Øko-Ø-færge" (Eco-Island ferry) and a project group was formed consisting of naval architects from Sweden and Denmark, university and shipyard representatives as well as specialists from research institutes. A project plan was drawn up for the project, where a full fire safety assessment according to SOLAS chapter II-2 Regulation 17 as well as LCC and LCA assessments were planned for the new *eco*logical and *eco*nomical island ferry.

A preliminary study [1] was carried out by SP Technical Research Institute of Sweden which was financed by Västra Götalandsregionen, Sweden, and supported by the rest of the consortia. It included investigations of national, European and international regulations as well as studies of the financial potential and potential market for lightweight island ferries in the region. The preliminary study also included search for further funding, which was allocated by The Danish Maritime Fund (Den Danske Maritime Fond), and development of the lightweight "Eco-Island ferry". This new ferry is meant to illustrate how an island ferry can be replaced by a more ecological and economic alternative. It was set out to replace the old Tun island ferry (Tunøfærgen), which has a route between the Hov and the island Tunö in Denmark. A prerequisite for the ship was to keep the same capacity as the Tun island ferry with 200 passengers and six cars (alternatively four cars and a truck). Using Fibre Reinforced Polymer (FRP) composite as shipbuilding material it is possible to reach a weight reduction of up to 60% [2], which would have significant positive effects on operational costs and environmental footprint. A ro-ro passenger ship with load-bearing structures in combustible FRP composite instead of in steel does although not comply with prescriptive fire safety requirements in the European passenger directive [3]. However, there is an opening for alternative fire safety design and arrangements in the EU directive which refers to Part F of the revised Chapter II-2 of SOLAS 1974 [4]. An evaluation of alternative design and arrangements may seem risky for a ship owner, both from a financial and a time perspective. The objective of this report is thus to show on the feasibility in reaching approval of an island ferry made in FRP composite.

1.2 Regulation 17

SOLAS (Safety of Life At Sea), adopted in 1929, is one of the most important directives for merchant ships on international waters. The convention was latest revised in 1974 and is with its updates and amendments still the regulation of practice. SOLAS consists of twelve chapters comprising issues such as construction, life-saving appliances, safety of navigation and other measures for maritime safety [5]. Fire safety has always been of great concern on merchant ships and for these matters chapter II-2 of the SOLAS convention is essential. To obtain sufficient fire safety according to SOLAS the fire safety objectives and functional requirements found in Regulation 2 need to be achieved; either by fulfilling the prescriptive requirements specified in parts B, C, D, E and G or by demonstrating that an alternative design and arrangements is at least as safe as if it would have been designed according to prescriptive requirements. The latter option is described in SOLAS Chapter II-2, Regulation 17 (part F), hereafter referred to as Regulation 17. Corresponding openings for alternative design exist also in other parts of SOLAS (e.g. for life-saving appliances, machinery and electrical installations) and is a step towards future Goal-Based Standards.

Prescriptive fire safety requirements stipulate structural decks and bulkheads to be made in non-combustible material but FRP composite is combustible. In line with Regulation 17, this could be treated as a deviation to prescriptive fire safety requirements and the Eco-Island ferry is hence an alternative fire safety design and arrangements. According to Regulation 17 an engineering analysis shall then be carried out based on the guidelines in MSC/Circ.1002 [6], hereafter referred to as Circular 1002. These guidelines open up for using performance-based methods of fire safety engineering to verify that the fire safety of an alternative design is equivalent to the fire safety stipulated by prescriptive regulations, a concept often referred to as the "equivalence principle". Since there are no general explicit criteria for the required level of fire safety, the fire safety in the alternative design needs to be compared to that of a prescriptive design. Accordingly, the prescriptive design is referred to as a reference design, complying with all the prescriptive fire safety requirements. The documented level of fire safety of the alternative design is therefore not absolute, but relative to the implicit fire safety of a traditional design, which is likewise a product of the implicit fire safety level in prescriptive regulations. Accounting for uncertainties when comparing levels of fire safety, the engineering analysis based on Regulation 17 (hereafter referred to as "Regulation 17 assessment") should with reasonable confidence demonstrate that the fire safety of the alternative design and arrangements is at least equivalent to that of a prescriptive design.

Performing a fire safety analysis according to Regulation 17 (part F) in SOLAS is in line also with the amended EU directive, as mentioned above. According to the EU directive the stipulated fire safety objectives and functional requirements can be achieved if the ship's design and arrangements, as a whole, comply with the relevant prescriptive requirements in the directive or if the ship's design and arrangements, as a whole, have been reviewed and approved in accordance with part F of the revised chapter II-2 in SOLAS 1974, which applies to ships constructed on or after 1 January 2003.

It was concluded in the preliminary study of the Eco-Island ferry project [1] that it would be more relevant to base a Regulation 17 assessment according to the EU directive on fire safety regulations as they are structured in SOLAS. In SOLAS the fire safety requirements have been rearranged to illuminate the objectives and functions of regulations, a structure adapted to allow for alternative performance-based design. Since the EU directive is based on and updated according to SOLAS, all prescriptive requirements in the EU directive are also found in SOLAS [1]. There should therefore not be any hindrance to use the prescriptive requirements in SOLAS, even when evaluating an alternative design and arrangements according to the EU directive. Due to incomplete updates of the EU directive there is although a hindrance to use the EU directive in the first place. From the unchanged Article 3 it is apparent that the EU directive does not apply to ships not made in steel or equivalent material. Even though the design and arrangements on the Eco-Island ferry will be adapted to provide safety equivalent to a steel construction and even though the ship will travel only in national waters, it has to become a SOLAS vessel to even be considered by the Swedish Transport Agency.

1.3 Procedure outline

The method of the engineering analysis required when laying claim to Regulation 17 is summarized in SOLAS [5], whilst detailed descriptions are found in Circular 1002 [6]. Briefly, the procedure can be described as a two-step fire risk assessment carried out by a design team. The two major parts to be performed are:

(1) the preliminary analysis in qualitative terms; and
(2) the quantitative analysis.

In the first part the design team is to define the scope of the analysis, identify hazards and develop design fire scenarios as well as develop trial alternative designs. The different parts of the preliminary analysis in qualitative terms are thereafter documented in a preliminary analysis report, which is the purpose of the report at hand. The preliminary analysis report needs an approval by the involved parties in the design team before it is sent to the Administration for a formal approval.

With approval from the Administration the preliminary analysis report documents the inputs for the next step of the Regulation 17 assessment, the quantitative analysis. The design fire scenarios are quantified at this stage and the outcomes are compared between the reference design (complying with applicable prescriptive requirements) and the trial alternative designs. The final documentation of the assessment shall demonstrate whether a safety level equivalent to that of a prescriptive design is achieved by the proposed trial alternative designs.

Regulation 17 was developed to undertake innovative design solutions, typically high atriums and long shopping promenades on cruise vessels, without compromising with fire safety. The regulation is in that sense employed to make safety more attractive, but it can also be used to make fire safety more cost-efficient, i.e. to accomplish the same level of fire safety at a lower cost or to increase fire safety at the same cost. In the present case, all steel divisions have been redesigned in Fibre Reinforced Polymer (FRP) composite. Above all, the material is combustible and the fire integrity will be fundamentally affected, which implies significant effects on fire safety. Making claim to Regulation 17, an evaluation of the alternative fire safety design should be based on Circular 1002, which has been identified as a "plausible worst-case" type of risk assessment [7]. However, in order to establish whether the fire safety of such considerable novelty can be regarded at least as safe as prescriptive requirements, it has been judged that the risk assessment needs to be more elaborated than what is outlined in Circular 1002 [7]. The required analysis process should not only comply with what is prescribed, it should also be sufficient to describe the introduced novelty in terms of fire safety. A more elaborated risk assessment has therefore been developed which comprises all the descriptions in Circular 1002 but brings the estimation and evaluation of fire risks to a higher level [8]. The method of the preliminary analysis in qualitative terms is succinctly delineated throughout the analysis process whilst more detailed explanations are given in *Appendix A. The revised approach*. The approach could advantageously be used also for other areas of SOLAS where corresponding analyses are made to evaluate alternative designs.

1.4 Formation of design team

The guidelines in Circular 1002 prescribe to form a design team to be responsible for the analysis and for co-ordinating the activities with regard to Regulation 17. The design team should mirror the complexity of the task in the sense that it should possess all the necessary competence to perform the assessment of fire safety. The design team selected for this project and the possessed expertise is presented in table 1.1.

Table 1.1. The selected design team for the Eco-Island ferry Regulation 17 assessment

Name	***Organisation***	***Profession / Competence***	***Role / responsibility***
Jens Otto Sørensen	Danish Yachts A/S	Mechanical Engineer, manufacture and ship design in FRP composite	Project leader of the Eco-Island ferry project, ship yard representative, ship design
Niels Kyhn Hjørnet	Yacht Design & Composite Engineering	Naval architect, ship design in FRP composite	Ship design
Mats Hjortberg	Coriolis AB	Naval architect, ship design in FRP composite, regulations, alternative design	Ship design, fire safety design
Henrik Johansson	Kockums	Naval architect, manufacture and ship design in FRP composite, fire safety	Ship design, fire safety design
Franz Evegren	**SP**	**Research scientist, risk management, fire safety**	**Primary contact person, co-ordinator of Regulation 17 assessment, fire safety design**
Malika Amen	SP	Project manager, FRP composite, fire safety	Co-ordination, Regulation 17 assessment, fire safety design
Michael Rahm	SP	Project manager, fire safety, mechanics, risk assessment	Regulation 17 assessment, fire safety design
Tommy Hertzberg	SP	Senior research scientist, fire safety, risk assessment, FRP composite	Regulation 17 assessment, fire safety design, quality assurance

2 Definitions of scope

This section describes the scope of the alternative design and arrangements followed by more detailed definitions of the prescriptive design and the foundational design and arrangements for the trial alternative designs (called a base design). A review the SOLAS fire safety regulations affecting the base design is thereafter documented.

2.1 Scope of the alternative design and arrangements

The Eco-Island ferry has been designed with the same capacity as the Tun island ferry (free translation of the actual Danish name Tunøfærgen), a reference ship. It is a Ro-pax ferry class D from 1993, designed to carry about 6 cars and 200 passengers (IMO# 9107875). The new ship was designed with the same capacity as the reference ship and approximately the same dimensions (LxBxD = 30.7x10x3.2 m). The two ferries are shown in figure 2.1 below.

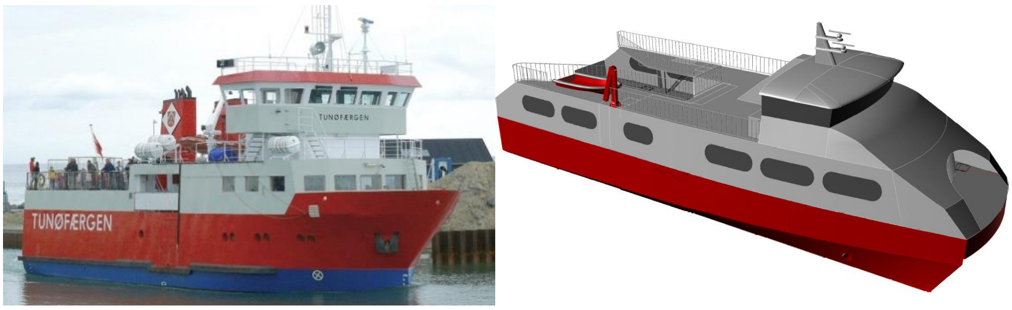

Figure 2.1. The present Tun island ferry (photo: Ulrich Streich) and the Eco-Island ferry.

The Tun island ferry has an ~1 h route between Hov and Tunø in Denmark and the number of passengers using the ship each year is approximately 50 000. It is a displacement ferry with a speed of 9.5 knots and the Eco-Island ferry is designed to keep the same speed. This is possible at a significantly lower engine power (220 kW compared to 590 kW) since structures are designed in FRP composite instead of in steel. Making the Eco-Island ferry in FRP composite instead of in steel, as the Tun island ferry, gives a displacement as specified in table 2.1 and a draft of 1.4 m. The number of crew of the Tun island ferry varies over the seasons but the Eco-Island ferry has been designed with 3 crew members on board.

Table 2.1. Weight specifications for the reference object, the Tun island ferry, and the Eco-Island ferry

Weight item	***Tun island ferry [kg]***	***Eco-Island ferry [kg]***
Lightweight	250 000	72 000
Ballast	33 900	0
Fuel & water	18 800	8 000
Stores	1 000	1 000
Passengers	15 000	15 000
Crew	225	225
Luggage	2 000	2 000
Cars	16 000	16 000
Deck cargo	3 075	3 075
Displacement	**340 000**	**117 300**

The scope of the alternative design and arrangements is hence an island ferry with the same capacity as the Tun island ferry but where all steel structures have been replaced by FRP composite. The prescriptive design (with steel structures) and the foundational arrangements for all alternative designs (the base design) are further described below. The general arrangement for the Eco-Island ferry is presented in *Appendix B. General arrangement*.

2.2 Definition of the prescriptive design and the base design

In a Regulation 17 assessment a number of trial alternative designs are defined and analysed. The starting point for the trial alternative designs is a base design. Applying different combinations of risk control measures (RCMs) to the base design makes up different trial alternative designs. The fire safety of these designs will be compared to that of a reference design which complies with all relevant prescriptive fire safety requirements, i.e. a prescriptive design). In the end it may prove that the base design provides sufficient safety on its own, due to existing safety measures installed beyond applicable prescriptive requirements. In that case the base design forms an acceptable trial alternative design. However, the normal case is that the base design needs additional RCMs in order to provide sufficient safety. Identified RCMs and distinguished trial alternative designs are further described in chapter 4 of this report whilst the prescriptive design and the base design are further defined subsequently. This is initiated by detailing the ship layout, followed by descriptions of the prescriptive design and the base design from a fire safety perspective.

2.2.1 Layout of the Eco-Island ferry

The Eco-Island ferry consists of a main deck and an upper deck on two pontoons. Between the pontoons there is also a wet deck, consisting of shallow void spaces. For the sake of simplicity in this report, the levels of the ship will although be referred to as deck 1, deck 2 and deck 3, starting from the floor of the pontoons. The wet deck will be referred to as deck 1.5. The notations are illustrated in figure 2.2 which also provides an overview of the layout of the ship.

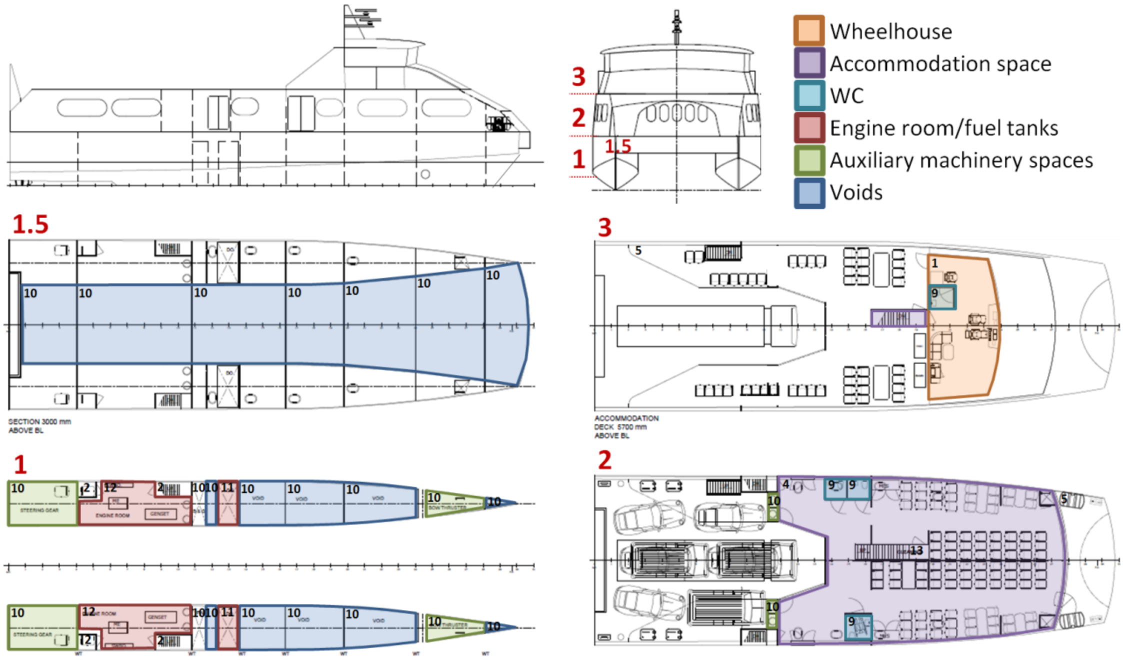

Figure 2.2. Overview of the ship where space classifications according to SOLAS II-2/9 are given and some spaces are coloured for guidance.

Starting from deck 1, the two pontoons are principally mirrored, starting with steering gear spaces (10; space category according to SOLAS II-2/9 for passenger ships carrying more than 36 passengers are given in parentheses) in the aft. These spaces are reached from the ro-ro deck through hatches which are generally locked. Thereafter follow the engine rooms (12) which each has two exits (unmarked in figure 2.2). One exit leads to a protected enclosure (2) with a ladder and a hatch to ro-ro deck. The other exit leads to a corridor with stairs to deck 2. Forward of the engine rooms is a fresh water tank (10) on starboard side and a black & grey water tank (10) on port side (unmarked in figure 2.2). After a small void space (10) follow the fuel tanks (11) on each side. Forward follow a number of void spaces (10), except the spaces with bow thruster equipment (10), marked green in figure 2.2.

Deck 1.5 consists of void spaces (10) made up from the transverse bulkheads and deck reinforcing the hull girder. The height of these spaces is approximately 1 m and they will only contain limited electrical equipment necessary for inspection and possibly pipe and cable penetrations.

Deck 2 (the main deck) mainly consists of a ro-ro deck in the aft and an accommodation area in the fore. The ro-ro deck is clearly classified as an "*Open ro-ro space*" according to SOLAS II-2/3.35, since it has an opening at one end and is provided with adequate natural ventilation in the sides and from above. Specific kinds of open deck spaces are not distinguished for passenger ships in SOLAS II-2/9; they simply fall under category (5) *Open deck spaces*. However, SOLAS II-2/20.5 specifies special requirements for ro-ro spaces on passenger ships carrying more than 36 passengers. On the Eco-Island ferry the ro-ro deck provides space for six cars or four cars and a truck (typically transporting garbage or delivering supplies or heating oil for apartments on the island). Between the ro-ro deck and the forward accommodation space there are small compartments containing fire rated ventilation ducts (10) to and from the engine room (this is better illustrated in figure 2.7). The accommodation space includes a boarding area and a seating area. In the boarding area there are three toilets (9) and exits to shore, ro-ro deck and to stairways (2) leading down to the engine rooms on each side. The seating area contains upholstered chairs for 100 passengers (including disabled), a cleaning cabinet (13) placed under the stairs to deck 3 and MES stations on port and starboard side (note that the cleaning cabinet is not marked in figure 2.2). The whole accommodation space is hence an assembly station and falls under category (4), but it is still referred to as the accommodation space. Forward the accommodation space exits to the foredeck (5) where there are life rafts and a deck space for management of the forward mooring arrangements.

Deck 3 contains an open deck space (5) with ~100 seats amidships and the wheelhouse (1) in the front. A passage from the wheelhouse to the exterior staircase on port side is an external escape route.

2.2.2 The prescriptive design

In the prescriptive design of the ship the hull, superstructure, structural bulkheads, decks, deckhouses and all other structures which are required to be made A-class are constructed in steel or other equivalent material. As a result of the space classifications outlined above, a number of fire safety requirements apply. As for passive fire protection, depicted in figure 2.3, 60 minutes of thermal insulation must be fitted in the ceiling of the engine rooms and also in the ceiling of the spaces with fuel tanks. In the engine rooms A-30 is required towards the staircases. Since all divisions on decks 1 and 1.5 are generally made in bare or painted steel, there are no relevant surface requirements. However, surfaces in all spaces on decks 2 and 3 must achieve low flame-spread characteristics. Furthermore, since the accommodation space is classified as an evacuation station, 60 minutes of thermal insulation is required towards the fore deck, ro-ro deck and enclosing the cleaning cabinet. The division of the accommodation space is one way to achieve the requirements to have redundant evacuation stations. It is since the life rafts on the fore deck are included in this evacuation plan that it must be thermally separated from the accommodation space. The division between the accommodation deck and the ro-ro basically forms a main vertical zone and divides the ship in two main fire zones.

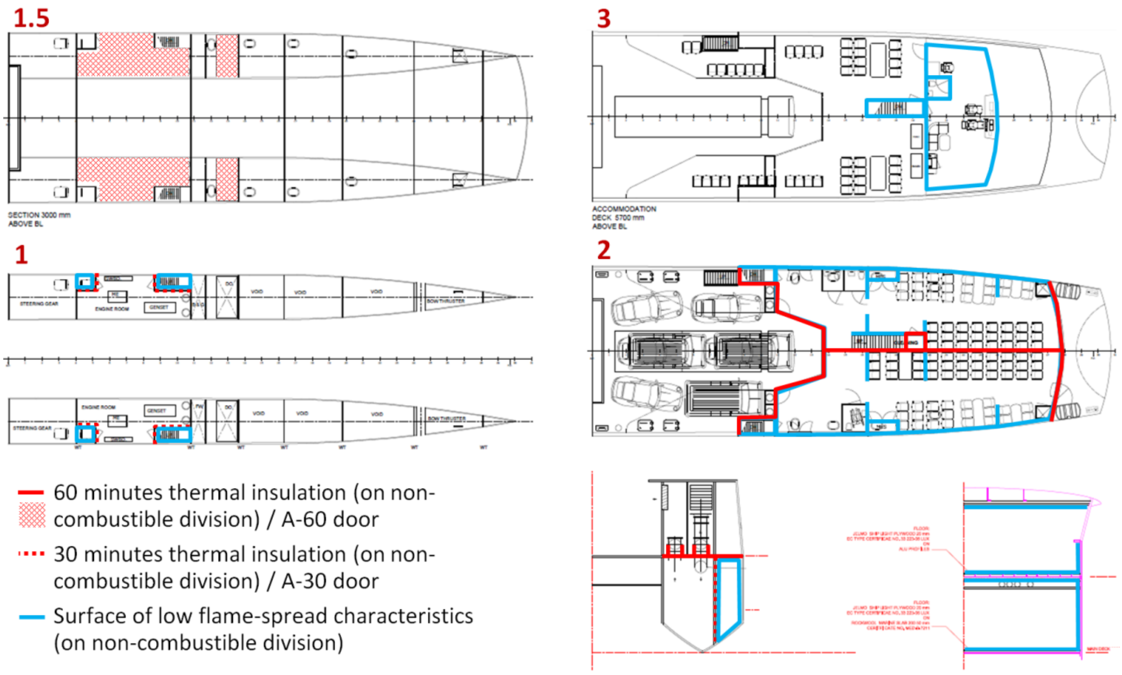

Figure 2.3. Overview of the passive fire protection of the prescriptive design.

The requirements regarding active fire protection includes detection systems, hydrants, fire hoses, portable extinguishers, sprinkler systems etc. All internal spaces of the ship are fitted with smoke detection systems, all except voids and tanks etc. Additional to the smoke detection systems there are visual fire (flame) detectors installed in the engine room and on ro-ro deck. The prescriptive design also includes different extinguishing systems, in accordance with the prescriptive SOLAS requirements as well as requirements of the Fire Safety Systems Code [7]. Internal spaces on deck 2 and deck 3 are protected with a high pressure water mist extinguishing system. The spaces on deck 1 (except engine room and stairs), deck 1.5 as well as casings from the engine room are not covered by sprinkler systems but reached manually from the fire main. The engine room is fitted with a water mist fire-extinguishing system.

2.2.3 The base design

The decks and bulkheads which otherwise are made in steel or equivalent material were designed in carbon fibre reinforced polymer (FRP), a material composition which is further described below. This construction material is, however, not intended for other structures prescribed to be made in "steel or equivalent material", such as ladders or doors. FRP composite is a good thermal barrier and has demonstrated good ability to contain a fire on its own [2, 9, 10]. However, since it makes the construction combustible and because of the predominant benefits in risk reduction compared to cost, some further mitigating efforts were implemented on a general basis. Below follow descriptions of the FRP composite constructions intended for the Eco-Island Ferry, the most important fire performance features of FRP composite and the implemented additional safety arrangements, which define the base design of the ship.

2.2.3.1 FRP composite and the construction materials of the base design

An FRP composite panel essentially consists of a lightweight core separating two stiff and strong fibre reinforced polymer laminates, which is illustrated in figure 2.4. The core material generally consists of PVC (polyvinyl chloride) foam or balsa wood and the face sheets are generally made by carbon or glass fibre reinforced polymer. When these laminates are bonded on the core, the composition altogether makes up a lightweight construction material with very strong and rigid qualities, which is further described in *Appendix C. FRP composite panels and fire performance*.

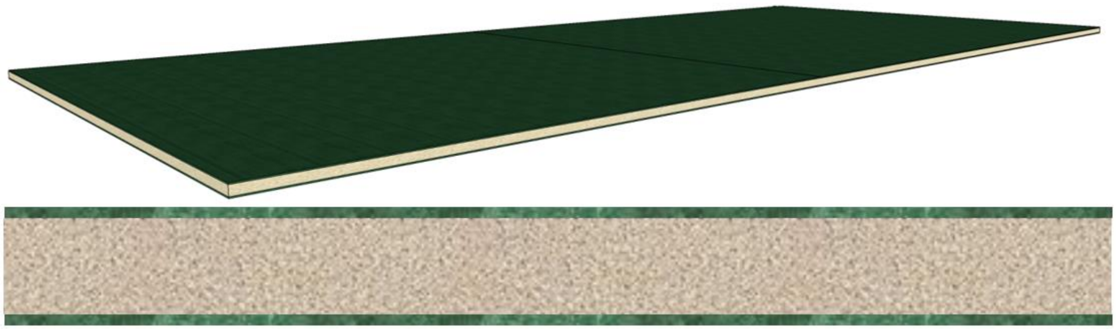

Figure 2.4. Illustration of an FRP composite panel (top) and a close-up on the lightweight core and the rigid and strong fibre reinforced laminates (bottom).

In summary, the performance of FRP composite when exposed to fire varies with the composition of core and laminates, mainly depending on the three conditions:

- thickness of face sheets: a thinner laminate gives a worse performing panel;
- density of core material: a lighter material gives a negative effect on the performance;
- type of plastic: a polymer with lower softening temperature gives less fire resistance.

A typical FRP composite set-up is a 50 mm PVC foam core (80 kg/m^3) surrounded by two 1.5 mm carbon fibre reinforced polymer laminates (approximately 2,100 kg/m^3). The total weight of such FRP composite is ~10.5 kg/m^2. This composite could replace a 7 mm steel plate which weighs 55 kg/m^2. Even if the composite requires additional fire safety measures the weight-loss is substantial when using FRP composite instead of steel. The strong and rigid characteristics, in conjunction with the weight-effectiveness, makes FRP composite a cost-effective alternative construction material for maritime load-bearing structures.

The Eco-Island ferry is intended to be built in a FRP composite consisting of carbon fibre reinforced laminates (Vinyl ester matrix and T300 fibres) on a PVC core (Divinycell). The used thickness and properties of laminates and cores depend on the required strength in different places of the ship. For example, the hull is generally designed with a 40 mm H100 core and laminates of 2.7 and 1.5 mm. Where ice reinforcement is necessary a higher density core (H200) and thicker laminates are used whilst the top sides above the water line are made with lower density core (H80) and a thinner laminates. In the superstructure bulkheads thin laminates are used in combination with a thicker core (60 mm H80) to provide for better acoustic and thermal comfort. The decks work as lateral stiffeners and are therefore generally of a more rigid construction (2,5 to 2,7 mm laminates on a 60 mm H130 core). Furthermore, a thin glass fibre laminate is applied to most exterior surfaces of the hull and superstructure to provide a rub layer.

2.2.3.2 Fire performance of FRP composite

The general material construction replacing steel in the ship is a sandwich construction with a lightweight core separating two laminates. As long as the core is intact and well adhered to both laminates, the structural strength of the material is not affected. The critical part of the construction regarding resistance to fire is hence the bonding between the core material and the laminate. The bonding softens and the structural performance deteriorates when the temperature in the bonding becomes critical; typically at 130-140ºC for a vinyl ester (and ~200ºC for a phenolic polymer matrix). Tests in the small-scale testing device called the Cone calorimeter (ref, ISO 5660) have shown that such critical temperature could be reached typically within one minute if the FRP composite is directly exposed to fire [11]. In addition, figure 2.5 shows that the material *ignites* very quickly when exposed to 50 kW/m^2 irradiation in the Cone calorimeter, an irradiance level typical of a large fire. Theoretically, a short period of such fire exposure might thus be critical for unprotected FRP composites, both from a structural strength perspective as well as from a fire perspective. However, large scale fire tests have shown that FRP composite structures may last much longer [2, 9, 10], both when exposed to local fire and fully developed fire. Further descriptions of the fire performance of FRP composite constructions are found in *Appendix C. FRP composite panels and fire performance*.

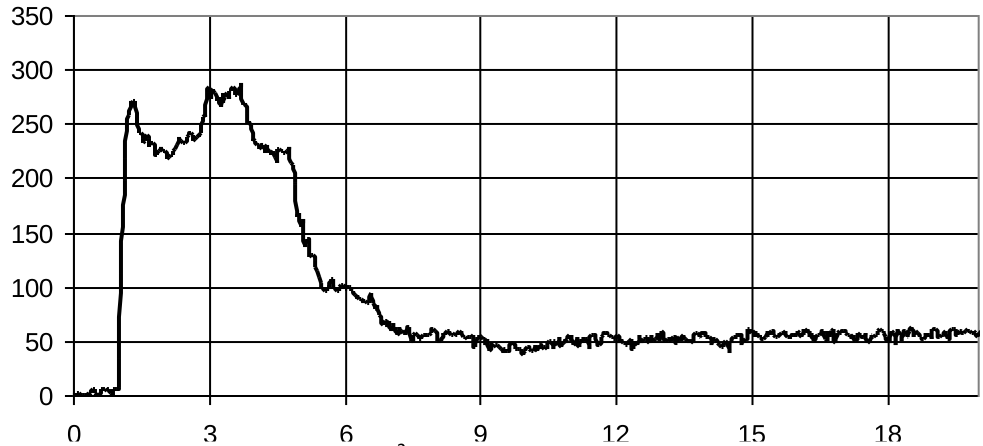

Figure 2.5. Heat release rate (kW/m^2) on the y-axis vs. time (minutes) on the x-axis, from FRP composite material when exposed to an irradiation of 50 kW/m^2 in the Cone calorimeter.

The structures replaced by FRP composite are generally required to achieve A-class standard. According to SOLAS II-2/3.2 this implies a "non-combustible" construction that will resist a 60 minute fire, represented by a temperature rise in a large furnace according to the standard temperature-time curve, as defined by ISO [12]. Depending on the following number, "A-X" (X = 0, 15, 30 or 60) requires fulfilment of a temperature requirement after X minutes on the side of the construction that is unexposed to fire. The fundamental condition for the FRP composite to achieve A-class standard is hence not so much the temperature requirement on the unexposed side but that structural resistance is maintained for 60 minutes.

To achieve this the FRP composite divisions could be insulated sufficiently to be classified as a Fire Resisting Divisions that maintains fire resistance for 60 minutes (FRD-60), according to the International Code of Safety for High-Speed Crafts [13]. This is illustrated in figure 2.6 where such construction was tested. The fire test required for an FRD in an High Speed Craft (HSC) is equivalent to the test required for A-class divisions in SOLAS ships, except for an additional load-bearing requirement. This requirement implies that FRD decks and bulkheads shall withstand the standard fire test while subject to transverse and in-plane loading, respectively. Even if this FRD-60 construction does not achieve the requirement on non-combustibility it will thereby fulfil the SOLAS requirements on fire resistance for an A-60 division. Furthermore, from the above discussion on critical temperature for softening of the FRP laminate-core interface, it is clear that the temperature on the unexposed side will, down to the high insulation capacity of the composite, be virtually at room temperature even after 60 minutes of fire. The heat from a fire will therefore to a larger extent stay in the fire enclosure and not so easily be transmitted to adjacent spaces.

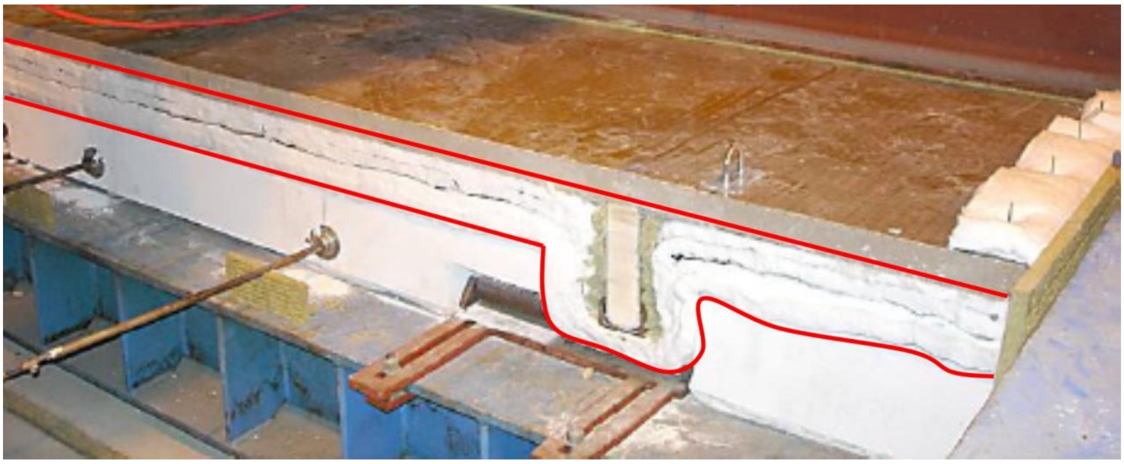

Figure 2.6. FRP composite deck with 60 minutes of thermal insulation, tested according to MSC.45 (65) [14].

Use of thermal insulation is one example of how the FRP composite could be protected to reach sufficient structural and integrity properties. The FRP composite could also be protected by combinations of passive and active risk control measures (RCMs) which altogether provides a solution with sufficient safety, e.g. surface treatment (achieving low flame-spread characteristics according to the FTP code [15]), limited insulation and sprinkler redundancy. The particular fire safety measures which are intended in the base design are further described below whilst potential additional RCMs are presented in chapter *4. Trial alternative designs*.

2.2.3.3 Fire protection of the base design

The base design of the ship fulfils applicable prescriptive requirements regarding the fire safety organization and fire fighting routines. Similarly, the active fire protection systems and equipment are in agreement with prescriptive requirements. All internal spaces of the ship therefore have smoke detection systems installed, all except voids having no source of ignition. The base design also includes different extinguishing systems, all complying with the prescriptive SOLAS requirements as well as requirements of the Fire Safety Systems Code [7]. Internal spaces on deck 2 and deck 3 are protected with a high pressure water mist extinguishing system but spaces on deck 1 (except engine room and stairs), deck 1.5 as well as casings from the engine room are not covered by sprinkler systems. These spaces are reached manually from the fire main. The engine room is fitted with a water mist fire-extinguishing system.

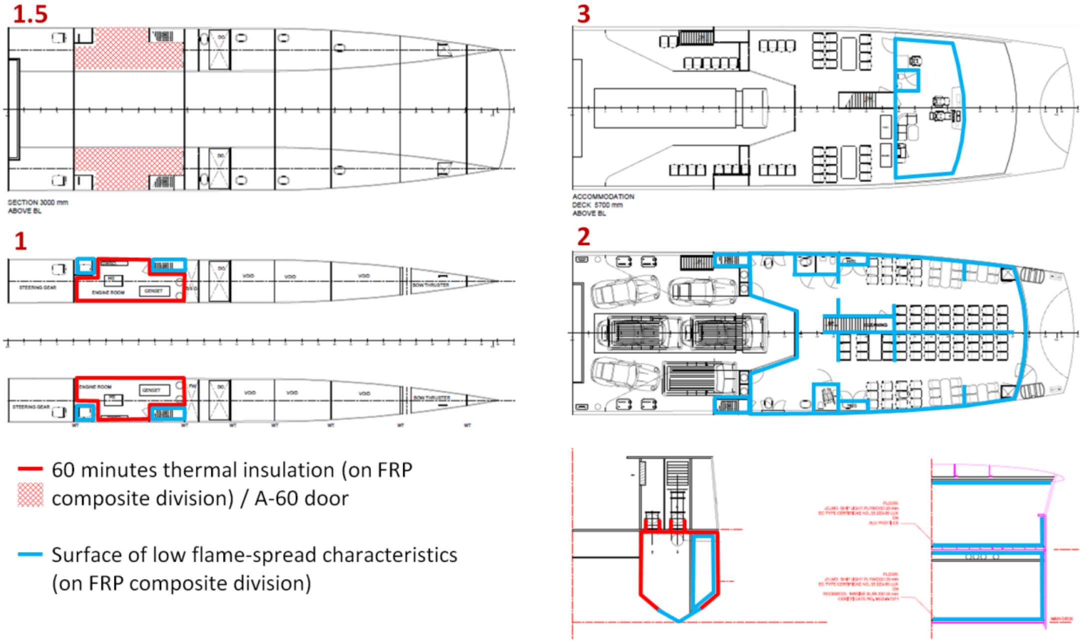

Figure 2.7. Passive fire protection of the base design.

Regarding passive fire protection, figure 2.7 illustrates how the base design in general was designed with safety measures of a rather low standard, lower than required by prescriptive requirements. A minimum level of essential passive fire protection was sought for the base design to provide for flexibility in the selection of additional safety measures.

Starting from deck 1, none of the spaces are designed with added passive fire protection except from the engine room and the stairways leading to it. Between the engine room and the adjacent compartments (steering gear, voids, stairways and water tank) in each pontoon there are A-class requirements (A-0, A-0, A-30 and A-0, respectively). In the base design the engine room will be fitted with 60 minutes of thermal insulation from the inside to provide 60 minutes of structural integrity. It will hence also give 60 minutes of protection against fire spread, which is otherwise only required against ro-ro deck (A-60). As in a prescriptive ship, the bulkheads will only be fitted with insulation down to 300 mm below the water line. The area below this level is covered with a surface of low flame-spread characteristics in accordance with the relaxed requirements for Aluminium hulls. However, this may need further attention since the FRP composite is not cooled by sea water and furthermore is combustible. For uniformity reasons the doors to the stairways and to the protected enclosures aft of the engine rooms will also be of A-60 category (A-30 required). However, the bulkheads are not thermally insulated from the stairways and protected enclosure sides. The surfaces in the stairways sides are simply of low flame-spread characteristics and contain no furnishings. Spaces classified in category (10) *Tanks, voids and auxiliary machinery spaces having little or no fire risk* were left with unprotected FRP composite in the base design (A-0 required in ceiling and bulkheads), which needs attention in the fire risk assessment. The spaces with fuel tanks are left without any passive fire protection in the base design even though A-60 is required towards the accommodation space above and A-0 toward the surrounding void spaces. The actual tanks are made in steel and occupy approximately one third of the spaces.

Moving up there is a requirement in SOLAS II-2/20.5 for ro-ro decks stating that the boundary bulkheads and deck of ro-ro spaces shall be insulated to A-0 or A-60 class standard, depending on the adjacent space. This means that the bulkhead forward towards the accommodation space and the deck towards voids, engine room and steering gear need to achieve fire resistance for 60 minutes and the divisions towards the accommodation space and the engine room also need to achieve 60 minutes thermal insulation. On a steel ship this is generally managed by insulating the inside of the steel decks and bulkheads. However, insulating the inside will not provide 60 minutes of structural integrity in case of a large fire on ro-ro deck. There are different solutions to address the A-60 requirements but none of which is predominant. The base design was therefore left without protective measures in this area whilst different RCMs for ro-ro deck will be evaluated further on in the Regulation 17 assessment. Doors from the ro-ro deck to the accommodation space were although made A-0, as all the doors where A-class requirements apply (A-0 is required for doors between accommodation space and stairways, accommodation space and wheelhouse, accommodation space and open deck as well as between wheelhouse and open deck whilst A-60 is required for doors between accommodation space and ro-ro deck, accommodation space and cleaning cabinet as well as between accommodation space and foredeck). In the accommodation space the toilets may be separated with B-0 divisions according to SOLAS II-2/9.2.2.3.2.2, since they are fully enclosed in the space. These divisions are although designed as the rest of the accommodation space, with FRP composite and surfaces of low flame-spread characteristics. The design also deviates from prescriptive requirements by not separating the cleaning closet and the foredeck with A-60 divisions. The accommodation space is also supposed to be separated from the wheelhouse by an A-0 deck.

On deck 3 the wheelhouse is supposed to be separated from the open deck space by A-0 divisions. The door follows this standard but the bulkheads are simply made in FRP composite with interior surfaces of low flame-spread characteristics. The same goes for the toilet in the wheelhouse which is supposed to be enclosed by A-0 divisions. The floor construction in the wheelhouse, and also in the accommodation area, consists of 20 mm plywood covered by a surface of low flame-spread characteristics.

A number of deviations from prescriptive regulations have already been identified above. Challenges against prescriptive requirements are further investigated in the following section. It is obvious that additional safety measures are required to achieve sufficient safety. The suitability of combinations of risk control measures needs to be further evaluated in the Regulation 17 assessment.

2.3 Fire safety regulations affecting the base design

By not complying with the prescriptive requirements, the base design does not achieve the same level of safety as is provided by a prescriptive design. It is therefore crucial to identify all deviations and determine how the deviations may have an effect on safety. This evaluation is presented subsequently, commencing with a background to and overview of the investigation. As part of the revised approach, the achievement of purpose statements was also judged independently (without regard to deviated prescriptive requirements), which is included in the discussions below. Some further evaluations were also made which are presented in *Appendix E. Additional regulation and fire safety evaluations*. These evaluations were added since use of FRP composite in shipbuilding is still relatively new and has limited field history regarding effects on fire safety and due to the rather large scope of the design and the deviations. The results from these additional investigations are summarized at the end of this chapter.

2.3.1 Background to and overview of the investigation of deviated requirements

At the beginning of the fire safety chapter in SOLAS, the goals of the chapter are defined through stated fire safety objectives. For these to be achieved, a number of stated functional requirements are embodied in the regulations of the chapter. Hence, the fire safety objectives and functional requirements are achieved by compliance with the prescriptive requirements. The fire safety objectives and functional requirements should although also be considered achieved if the ship has been reviewed and approved in accordance with Regulation 17. This regulation gives a possibility to deviate from prescriptive fire safety requirements on condition that a degree of safety is provided not less than that achieved by complying with prescriptive requirements.

The fire safety chapter is structured as illustrated in figure 2.8, where the fire safety objectives set out the goals of the chapter and the functional requirements are embodied in the following regulations in order to achieve the goals. The following regulations cover a certain area of fire safety, e.g. ignition, containment or fighting of fire, which is defined by a purpose statement at the beginning of each regulation. The purpose statement consists of a regulation objective and the functional requirements to be achieved by that regulation. Thereafter follow prescriptive requirements in each regulation.

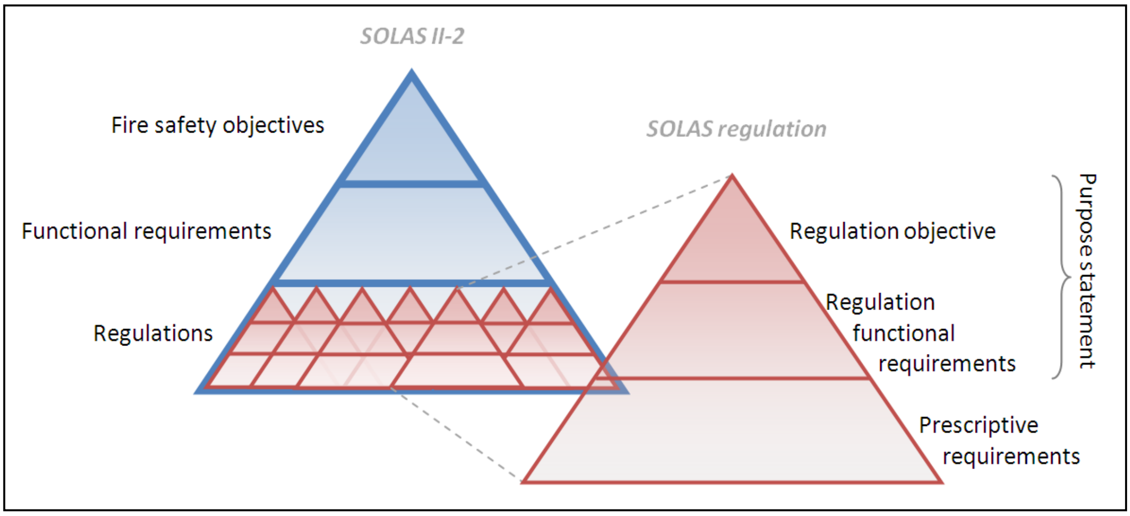

Figure 2.8. Each regulation in SOLAS II-2 consists of a purpose statement and prescriptive requirements. The purpose statements comprise regulation functional requirements and an individual regulation objective which sets out the objective of the functional requirements.

The fire safety objectives and functional requirements of the fire safety chapter are meant to define fire safety, which hence also defines how safety is measured. This is further defined through the functional requirements in the regulations, in light of the regulation objectives. How well these functional requirements must be achieved is although determined by the performance of a reference design, complying with all the applicable prescriptive requirements. Compliance with the prescriptive requirements is thus only one way to meet the functional requirements, as stated in paragraph 6.3.2 in Circular 1002. Since the regulation functional requirements define the measures by which safety may be assessed it is highly important to identify which ones the alternative design and arrangements may affect the achievement of. Deviations from prescriptive requirements must therefore be identified and their purposes clarified by recognizing the associated functional requirements. Onwards the functional requirements of the deviated prescriptive requirements will be used along with the fire safety objectives (of the whole fire safety chapter) to define performance criteria.

Effects on the prescriptive safety level, posed by an alternative design and arrangements, can hence be assessed by how achievement of relevant functional requirements is affected. If the deviations are great, the ship may although not achieve the functional requirements of each deviated regulation as well as a prescriptive design. Performing better in other areas may although compensate for such deficiencies. To take this into consideration it is necessary to take a broader approach to assess safety than to evaluate each safety function individually. It is although recommendable if effects on safety from deviations can be managed within the scope of each regulation separately, since this will simplify the evaluation process.

A scrutiny of the fire safety regulations in SOLAS II-2 was carried out where the regulations were divided according to figure 2.8 above and where deficiencies in the base design were identified. Identified deviations to prescriptive requirements are summarized in table 2.2 along with associated regulation functional requirements and regulation objectives. The deviations are thereafter briefly described in the following paragraphs. The full scrutiny of all regulations is lain out in *Appendix D. Evaluation of prescriptive requirements and associated functional requirements*.

Table 2.2. A summary of the challenged SOLAS II-2 regulations and a comment on how the base design challenges prescriptive requirements and purpose statements.

SOLAS II-2	***Regulation Objective (RO)***	***Regulation Functional Requirements (RFR)***	***Comment on how the base design affects the regulation***
Part B	**Prevention of fire and explosion**		
Reg. 5 Fire growth potential	Limit the fire growth potential in every space of the ship.	(1) Control the air supply to the space; (2) Control flammable liquids in the space; (3) Restrict the use of combustible materials.	Unprotected or insufficiently protected FRP composite surfaces could be a fire risk. If open deck is considered a space, unprotected external surfaces challenge RFR 3.
Reg. 6 Smoke generation potential and toxicity	Reduce the hazard to life from smoke and toxic products generated during a fire in spaces where persons normally work or live.	Limit the quantity of smoke and toxic products released from combustible materials, including surface finishes, during fire.	Unprotected interior FRP composite surfaces in steering gear may be argued to deviate from Reg. 6.2.1, even if the surfaces are without finish.
Part C	**Suppression of fire**		
Reg. 9 Contain-ment of fire	Contain a fire in the space of origin	(1) Subdivide the ship by thermal and structural boundaries; (2) Boundaries shall have thermal insulation of due regard to the fire risk of the space and adjacent spaces; (3) The fire integrity of the divisions shall be maintained at openings and penetrations.	Load-bearing bulkheads, decks, and where necessary also internal bulkheads, made in combustible material deviates from the A and B class definitions. Insufficient thermal insulation is provided in several places.
Reg. 11 Structural integrity	Maintain structural integrity of the ship, preventing partial or whole collapse of the ship structures due to strength deterio-ration by heat.	Materials used in the ships' structure shall ensure that the structural integrity is not degraded due to fire.	Reg. 11.2 is deviated as it states structures to be constructed in "steel or other equivalent material", which is defined as non-combustible (Reg. 3.43).

Part D	Escape		
Reg. 13 Means of escape	Provide means of escape so that persons on board can safely and swiftly escape to the lifeboat and liferaft embarkation deck	(1) Provide safe escape routes; (2) Maintain escape routes in a safe conditions, clear of obstacles; (3) Provide additional aids for escape, as necessary to ensure accessibility, clear marking, and adequate design for emergency situations.	Reg. 13.5.1 requires thermal insulation separating ro-ro deck from spaces below, which is not fulfilled. From SOLAS III it is implied that two alternative evacuation stations should be provided, which is not fulfilled.
Part G	**Special requirements**		
Reg. 20 Protection of vehicle, special category and ro-ro spaces	Provide additional safety measures in order to address the fire safety objectives of this chapter for ships fitted with vehicle, special category and ro-ro spaces	(1) Provide fire protection systems to adequately protect the ship from the fire hazards associated with vehicle, special category and ro-ro spaces; (2) Separate ignition sources from vehicle, special category and ro-ro spaces; (3) Adequately ventilate vehicle, special category and ro-ro spaces.	The structural fire protection required by Reg. 20.5 is not provided in the base design; partly since the FRP composite doesn't fulfil A class standard and partly due to lack of thermal insulation towards accommodation space, overhang and engine room.

2.3.2 Regulation 5: Fire growth potential

This regulation oversees materials in spaces with the intention to limit the fire growth potential. All prescriptive requirements of regulation 5 considering enclosures are considered complied with but the ship design in FRP composite will still have implications for the fire growth potential. Reg. 5.3.2.4.1 requires certain divisions faced with combustible materials to achieve low flame-spread characteristics, which is why the accommodation space, stairways and wheelhouse are designed with such surface material. For the same reason tanks, voids and auxiliary machinery spaces were left with unprotected FRP composite in the base design. However, these uncovered divisions are normally made in non-combustible material. Similarly, constructions with surfaces of low flame-spread characteristics are normally not constructed with a combustible FRP composite just underneath. This fire hazard could affect the fire growth potential and needs attention in the fire risk assessment.

Furthermore, the third regulation functional requirement (Reg. 5.1.3) could be claimed challenged as it states the use of combustible materials shall be restricted. The definition of a non-combustible material is given in Regulation 3.33 in SOLAS and defines it as a material that neither burns nor gives off flammable vapours when heated to 750°C. FRP composite laminates generally give rise to pyrolysis gases when exposed to temperatures above 500°C and it could therefore be argued that the amount of combustible material is increased when exchanging steel with FRP composite. The base design will although contain the same approved materials for linings, grounds, draught stops, ceilings, faces, mouldings, decorations, veneers, etc. as those used in a traditional (prescriptive) design. These are also the materials that will govern the growth phase of a fire, together with interiors. In this sense, the base design will not add to the fire growth potential in interior spaces. If open deck is considered a space though, the unprotected combustible external surfaces could give reason to assert deviation from the regulation functional requirement. When scrutinizing Regulations 5 and 6 it is although important to realize that "smoke production" and "smoke generation potential and toxicity" imply different things. They have to do with the quantity and the quality of the smoke, respectively. The former is mainly covered in Regulation 5 (fire growth potential) whilst the latter mainly has to do with the individual material characteristics, covered by Regulation 6. One could say that

Regulation 5 manages so that an unrestricted amount of kilos of combustible materials do not catch on fire and Regulation 6 manages the potential of each kilo that can be involved in a fire. Hence, a consequence of increased fire growth potential is increased smoke production. This, however, is not as relevant of a problem to consider for external fires where smoke management is not critical. Fire spread on combustible external surfaces must although be given due regard in the fire risk assessment.

2.3.3 Regulation 6: Smoke generation potential and toxicity

Similar to Regulation 5, the scope of Regulation 6 is also enclosures and the first stages of a fire, which is when people could be exposed to toxic smoke. All materials involved in a fire will contribute to the production of toxic smoke and many materials are therefore controlled by the IMO. In order to reduce the hazard to life, only approved linings, floors, surface materials etc. are used in both the base design and the prescriptive design. However, in the spaces where the FRP composite is left unprotected, Regulation 6.2.1 may be claimed deviated. Even if this regulation only applies to surface finishes it may be argued that a non-combustible material is implied underneath. The generation and toxicity of smoke may therefore not be limited to the same extent as in a prescriptive design in these spaces. Reflecting in what spaces such deviation would be relevant, exterior spaces should not be considered since smoke production is not critical outside. The aim of the regulation is spaces where people work or live, which excludes void spaces. The only spaces left without a surface of sufficient quality is the steering gear and bow thruster spaces, if those are considered as spaces where people work.

2.3.4 Regulation 9: Containment of fire

This regulation prescribes bulkheads and decks to be made up by A class divisions, which implies steel or equivalent material should be used (except insulation). Reg. 3.43 defines steel or equivalent material as a non-combustible material which, by itself or down to insulation provided, has structural and integrity properties equivalent to those of steel. As a result of this definition doors, pipes, windows etc. are also generally required to be made in metal when penetrating A class divisions. To fulfil the A class requirement (and in some cases requirements on thermal insulation) some of the FRP composite divisions and penetrations have been fitted with protective thermal insulation. Most boundaries although are insufficiently insulated, according to *2.2.3 Fire protection of the base design*. Even if integrity properties in divisions would be achieved, using combustible FRP composite in A divisions is a deviation.

In case of an engine room fire, the base design achieves equal structural properties and the added thermal insulation in divisions and penetrations makes it exceed the requirements on integrity by all means. Especially where only A-0 divisions are required and there is no obligation to insulate divisions or to use fire rated penetrations. Thanks to improved thermal insulation, the engine room in the base design will contain a fire in its origin better than the reference design. However, it is a deviation that the divisions surrounding the engine room are only protective one way, i.e. if a fire starts in the engine room and not if it starts in the surrounding compartments.

According to Reg. 9.6.6.1 boundary bulkheads and decks facing the cargo deck need to be insulated to A-60 class standard, which is not fulfilled in the base design (the same requirements is found in Reg. 20, where it is further commented). Reg. 9.7 further describes that ventilation ducts have to be of non-combustible material. As the ducts in the base design are made of FRP composite, this prescriptive requirements is also deviated.

2.3.5

Regulation 11: Structural integrity

The prescriptive requirement in SOLAS II-2/11.2 states:

> "The hull, superstructures, structural bulkheads, decks and deckhouses shall be constructed of steel or other equivalent material. For the purpose of applying the definition of steel or other equivalent material as given in regulation 3.43, the 'applicable fire exposure' shall be according to the integrity and insulation standards given in tables 9.1 to 9.4. For example, where divisions such as decks or sides and ends of deckhouses are permitted to have 'B-0' fire integrity, the 'applicable fire exposure' shall be half an hour."

Again, the requirement to make structures in steel or other equivalent material cannot be complied with, as it interprets as non-combustible material. A severe fire could cause the structure to deform when the thermal insulation is no longer enough to keep the temperature sufficiently low. In the worst-case scenario it could bring about a local collapse when the FRP laminates detach from the core. However, the good structural behaviour of the FRP composite in a real fire, even with local delamination occurring in the composite due to high temperature, was documented at SP in a full scale cabin fire test [16]. It is worth remembering that also a steel construction suffers from strength deterioration, and particularly deformation problems, when heated.

2.3.6 Regulation 13: Means of escape

According to SOLAS II-2/13.3.1.3, all stairways in accommodation spaces, service spaces and control stations shall be of steel frame construction or equivalent material. The same applies to stairways and ladders in machinery spaces, SOLAS II-2/13.4.1. Such constructions are not within the scope of the FRP composite design of the Eco-Island ferry and the regulations are thus fulfilled. The steering gear room only has one escape route, which is although acceptable since the maximum distance to the door, in this case a hatch, is less than 5 meters (see SOLAS II-2/13.4.2.3). Safe escape from the engine room is provided via a ladder in a protected enclosure in combination with a regular stairway (an alternative according to SOLAS but required by the national regulations of Sweden [17]), both found behind A-60 doors. The requirements in SOLAS II-2/13.5.1 imply that the escape routes from ro-ro deck must be thermally protected from fire on the decks below; in this case by A-0 divisions against the void spaces and by A-60 divisions against the steering gear and the engine room. The separations against steering gear and void spaces do not fulfil these requirements. Furthermore, from SOLAS III it is apparent that two alternative evacuation stations must be provided. This is not fulfilled by the base design with only one large evacuation station, i.e. the accommodation space. Furthermore, the life rafts on foredeck must be protected from a fire in the accommodation space, which is not achieved in the base design.

2.3.7 Regulation 20: Protection of vehicle, special category and ro-ro spaces

This regulation describes requirements for ventilation, alarm and detection systems, fire extinguishing equipment and structural requirements for spaces with vehicles. In Reg. 20.5 it is stated that boundary bulkheads and decks of the ro-ro space must achieve A-60. The structural fire protection can although be reduced to A-0 where the adjacent spaces are of category 5, 9 or 10, i.e. against steering gear and void spaces. Except from not fulfilling A class standard the base design does not achieve A-60 towards the engine room, the accommodation space and the overhang (the open deck space above parts of the ro-ro deck).

The fixed detection and alarm systems on ro-ro deck will be according to prescriptive requirements. The ship will furthermore be designed with an approved fixed water-spraying system for the vehicle space and an appropriate drainage system. As on a steel ship, the vehicle deck will be equipped with fire extinguishers, water-fog applicators and portable foam applicator according to prescriptive requirements.

Even if not required from prescriptive requirements, it might prove necessary from the risk assessment to fit the new Eco-Island ferry with additional active fire extinguishing equipment on the outside of the ship superstructure to ensure that fire does not spread from the vehicle space.

2.3.8 Further regulation and fire safety analyses

The preceding evaluation of the base design has been delineated to document affected regulations with a starting point in prescriptive requirements and associated purpose statements. In particular the requirements on “non-combustible” and “steel or equivalent material” cannot be achieved by the novel material, even if the accomplished safety may be sufficient. It was also found that the current steel-based regulations are not fully applicable for this kind of design as they do not consider combustible exterior surfaces. However, the high level of innovation in the present design case invokes further evaluations of how the base design affects the implicit level of fire safety in the regulations [7]. For this reason, evaluations have been performed revealing effects on the general fire safety objectives and functional requirements stated in SOLAS II-2/2, which are significant as they set out the safety targets for the whole chapter. In addition, effects on the structure of the fire safety prescribed in regulations and effects on different properties represented in current requirements have been scrutinized. This way innate effects on the implicit level of fire safety in regulations have been identified. The above analyses were complimented with a general evaluation of how the novel structural material may affect different stages of a fire development in the base design. These additional regulation and fire analyses are documented in *Appendix E. Additional regulation and fire safety evaluations* and summarized below.

2.3.9 Summary of the results from additional regulation and fire safety analyses

The additionally performed analyses revealed several important effects on the implicit level of fire safety that need to be verified. When it comes to the fire safety objectives in SOLAS II-2, the base design may fulfil some of the objectives superior to a traditional design down to its improved thermal insulation. The focus on safety of human life in the fire safety objectives makes it topical to address, not only the safety of passengers, but also the safety of fire fighters and crew. Investigating the functional requirements for the whole fire safety chapter in SOLAS especially indicated that the risk when adding combustible materials needs to be accounted for.

Effects on the fire safety structure mainly concerned the exposure and effect parts of the fire protection strategy and invoke thorough verification since the changes will affect many protection chains. The following analysis of fire safety properties showed that in particular human intervention, complexity in the fire protection strategy, reliability and vulnerability will be affected. The implications for safety may, however, not be very significant for all of these properties.

When the revealed differences were put in the context of fire dynamics it was established that the ignition and first stages of a fire in an enclosure will be unaffected by a change to FRP composite if it is insulated or at least protected. In case the circumstances allow a fire to progress, it will reasonably be better contained in the structure within the first 60 minutes in a FRD-60 compartment. In case of fire that ability could e.g. give the advantage of an increased time for escape as the temperature in the staircases and escape routes would be significantly lower. If FRP composite surfaces are only protected with low flame-spread characteristics and there is fuel available they may provide fuel to an already on-going fire. The conditions in the base design if a fire develops past 60 minutes may although be worsened, in comparison with a traditional design. Fire safety will also be negatively affected in case a fire includes external surfaces, which go from being non-combustible in a steel design to combustible but protected in the base design.

3 Development of fire scenarios

Understanding and documenting differences in fire safety between the base design and the reference design, processes which have been described above, are crucial steps to establish the needs for verification. Thereafter the verification process continues to estimate the possible effects from these differences on fire safety by incorporating them in fire scenarios. The development of fire scenarios is initiated by identifying and tabulating fire hazards. Thereafter the fire hazards are enumerated and rated in different ways. Fire hazards are then selected to make up design fire scenarios, which are thereafter specified. These processes and their results are further described below.

3.1 Identification of fire hazards

A Hazid workshop was held at Kockums in Malmö 7 February 2012. A Hazid, or hazard identification, is a systematic brainstorming session where the fire safety of each concerned space is thoroughly investigated to identify fire hazards, i.e. what could give rise to fire and burn in different stages of a fire in the spaces. Critical objects and conditions significant in different stages of the fire development are also to be identified. The process was carried out by the multidisciplinary design team selected for this specific design case and resulted in a tabulation of fire hazards, as presented in *Appendix F. Data from fire hazard identification*.

3.2 Enumeration of fire hazards

According to Circular 1002 the identified fire hazards should be grouped into one of the three incident classes localized, major or catastrophic. These incident classes are meant to signify the effect zone of the fire hazards, i.e. if the fire is confined in an area, ship or spreading outside of the boundaries of a ship. The instruction to tabulate fire hazards into these incident classes can, however, seem quite illogical with the standard definitions of hazard and incident within risk management. A hazard is namely merely a source of danger whilst the incident classes represent degrees of consequences, which will depend on the existence and function of safeguards. With this perspective, the hazards do not have to be related with the possible outcomes. It is rather the probability of functioning safeguards and the potential consequences which together constitute the possible outcomes, i.e. what is generally called risk.

If fire hazards identified in the concerned spaces after all are to be enumerated in the above specified incident classes, which is instructed by Circular 1002, one could claim that the first three columns in *Appendix F. Data from fire hazard identification* (ignition sources, initial fuels and secondary fuels) are localized fire hazards and that the extension potentials are major fire hazards. However, since the judgement is based only on identified fire hazards within spaces and extension potentials (i.e. propagation of fire to adjacent spaces), truly major or catastrophic incidents will not be identified. Catastrophic incidents could obviously appear if fuel is provided and if the fire is allowed to continue, i.e. depending on the function of safeguards. In the present case, however, only localized and major fire incidents have been considered since the scope of the alternative design and arrangements makes it reasonable to assume that the introduced fire hazards pose threats essentially within the ship vicinity.

The tabulation in *Appendix F. Data from fire hazard identification*, hence, provides an enumeration of the identified fire hazards as required. However, what Circular 1002 could be aiming at when stipulating an enumeration into incident classes, and what is more useful, is to rather identify and categorize the plausibly worst fire developments in the spaces, based on the identified fire hazards. It can be said to constitute some form of fire hazard rating of the concerned spaces, since only plausibly worst consequences are considered and probability thereby is included to a very limited extent. Despite this, and although it is founded on value judgement, it provides an indication of the fire risks as perceived by the design team. The ratings of the plausibly worst fire developments were divided in the two categories (A) Amount of combustibles and (P) Potential fire growth rate. The ratings were made from 1 to 5 for each space in the base design, based on the performed identification of fire hazards. The fire hazard ratings are listed in table 3.1 below.

Table 3.1. Fire hazard ratings for the spaces in the base design

Deck 1	***A***	***P***	***Deck 1.5***	***A***	***P***	***Deck 2***	***A***	***P***	***Deck 3***	***A***	***P***
Steering gear space	2	2	Voids	2	2	Ro-ro deck	5	4	Wheelhouse	3	3
Engine rooms	4	5				WCs	2	2	Open deck space	4	2
Water tanks	1	1				Ventilation casings	2	3	WC	2	2
Fuel tanks	5	2				Accommodation space	4	4			
Void spaces	2	2				Fore deck	4	2			
Bow thruster spaces	2	2									
Stairways	2	2									

A: Amount of combustibles (1-5)
P: Potential fire growth rate (1-5)

The rating of fire hazards given in table 3.1 most likely serves the purpose of the prescribed enumeration of fire hazards in Circular 1002. It is useful when selecting fire hazards to form design fires and event trees, which will define the fire scenarios. The table describes the conditions for a fire starting in the concerned spaces. However, in the Hazid there were also fire hazards identified with regards to fire spread, which influenced the selection of fire hazards.

3.3 Selection of fire hazards

In the next step of the procedure to develop design fire scenarios, fire hazards are to be selected to form design fires and event trees. A design fire is a description of the development and spread of fire for use in a fire scenario. An event tree describes different courses of development with failure modes and probabilities. Together with a design fire, failure modes will make up fire scenarios, from which design fire scenarios could be chosen to cover all fire scenarios. In the present case the ambition is although to quantify a larger range of fire scenarios.

When selecting the fire hazards to be considered in the design fires and amongst the failure modes, primarily differences between the prescriptive design and the base design need to be included. Thereafter, fire hazards that significantly will affect the fire development should be taken into account. Finally it should be a general goal to include as many of the identified fire hazards as possible. Depending on the depth of the assessment, this can invoke more than one fire scenario to be determined.

In order to include the above aspects, all of the previously identified fire hazards were reviewed with help from the Procon list (*Appendix G. Procon list*) to distinguish the fire hazards differing between the designs and the ones with great potential to affect a fire development. This process also worked as an input to the fire hazard rating in table 3.1. Concurrently, target locations affecting failure modes were recognized for all spaces along with their number of exits and whether the space is an evacuation route. As in the previous process, priority was to distinguish fire hazards differing between the base design and the reference design. A summary of the results is presented in table 3.2.

Table 3.2. Summary of whether the spaces are evacuation routes and their number of exits, along with target locations affecting failure modes

	Evac.	*Exits*	*Aut. ext.*	*Door*	*Win.*	*Det.*
Deck 1						
Steering gear spaces	No	1	No	No*	No	Yes
Engine room	No	2	Yes	Yes	No	Yes
Water tanks	No	N/A	No	No	No	No
Fuel tanks	No	N/A	No	No	No	No
Bow thruster spaces	No	1	No	No*	No	Yes
Void spaces	No	N/A	No	No	No	No
Stairways	Yes	2	No	Yes	No	Yes
Deck 1.5						
Voids	No	N/A	No	No	No	No
Deck 2						
Ro-ro deck	Yes	2	Yes	N/A	N/A	Yes
WCs	No	1	Yes	Yes	No	Yes
Ventilation casings	No	N/A	No	No	No	No
Accommodation space	Yes	2	Yes	Yes	Yes	Yes
Fore deck	No	1	No	N/A	N/A	No
Deck 3						
Wheelhouse	No	2	Yes	Yes	Yes	Yes
Open deck space	No	1	No	N/A	N/A	No
WC	No	1	Yes	Yes	No	Yes

*** Compartment is accessed through a hatch from the deck above**

Table 3.2 shows differences between the spaces involved in the base design and the reference design. However, as mentioned above, the main priority in the preceding processes has been to identify differences between the base design and the reference design. The most significant differences to consider when forming design fire scenarios is obviously the fact that divisions include combustible materials. This is the same for all involved spaces and was included in the previous fire hazard rating. Differences to consider when forming the event trees are particularly fire hazards represented amongst the target locations which affect failure modes. A difference which may be significant in a fire scenario is for example the fact that there in many cases are non-insulated combustible divisions in the base design where A-class divisions are required in prescriptive requirements.

The next action in the process of selecting fire hazards is to group spaces with similar characteristics to narrow down the number of design fire scenarios and simplify the following quantitative analysis. Design fires will be developed for the groups of spaces with similar fire characteristics. However, dissimilarities may appear in e.g. heat release rate, depending on diverging floor areas. Simplifications and constructive (preferably conservative) assumptions are therefore necessary in order to simplify the proceeding analysis. With the revised approach (see *Appendix A. The revised approach*) all spaces on the ship should be arranged in groups of spaces with similar fire hazards (even if spaces with the least foreseen differences in fire safety may not be necessary to prioritise). Following this selection process and based on the previous tables, seven groups of spaces were distinguished:

1. Accommodation space
2. Engine rooms
3. Auxiliary machinery spaces
4. Void spaces

5. Wheelhouse
6. Ro-ro deck
7. Stairways

These groups have similar conditions for fire scenarios, as further specified below, and each group can be said to be represented by a fictitious representative space. Each representative space is assigned a relevant and plausibly worst-case uncontrolled design fire as well as failure modes affecting the fire development. The design fire for each representative space was selected based on the largest amount of combustibles with the highest potential fire growth rate amongst the spaces in each category, as specified in table 3.1. Considerations were also made to include potential effects from fire spread from other areas, which could affect the fire development. Furthermore, conservative assumptions were made regarding target locations in order to select influencing failure modes, and regarding the size of the compartment. The relation to evacuation routes and the size of the floor area also worked as input to the above categorization, as further described below.

3.4 Specification of fire scenarios

As a result of the revised approach, not only a few design fire scenarios will be specified. Instead the conditions and characteristics defining a large range of the possible fire scenarios in the above selected groups of spaces will be specified. As described above, each group of spaces is tied to a representative space which is assigned the worst selection of fire hazards from the spaces. Hence, when it comes to implementing further active and passive risk control measures, all spaces in each category will be treated equally (as if they contained the worst fire hazards).

A design fire can be said to be the fire one can expect when all safety measures are eliminated, or the fire in a certain environment that the design should be able to manage with the implemented safety measures. Based on the defined design fire it is possible to identify suitable passive and active risk control measures for each space. It is also possible to evaluate effects on life safety, e.g. through evacuation analysis. Hence, in the task of gaining sufficient safety by implementing alternative risk control measures, the definition of design fires is central. At this stage of the Regulation 17 assessment the design fires are qualitatively defined by what could ignite and burn in different stages of a fire development. The potential fuels in each space group were therefore recognized and specified below. Likewise, the failure modes and conditions that could affect the progressing fire and that determine the range of fire scenarios were recognized from each space group. Subsequently, the following potential fuels and conditions were recognized for each representative space:

1. ignition sources: potential ignition sources, i.e. high temperatures and other energy sources in contact with potential fuels are of interest as well as exposure time and area;
2. initial fuels: potential initial fuels, their state (solid, liquid, gas, vapour, spray), amount etc. are of interest;
3. secondary fuels: potential secondary fuels, their state, proximity to initial fuels, amount, distribution etc. are of interest;
4. extension potential: structures and areas to where fire might spread beyond the compartment of fire origin;
5. target locations: target items or areas associated with the listed critical factors, e.g. if oxygen supply through a door or the door integrity is crucial for the fire development, the door should be identified as a target location; and
6. critical factors: important factor associated with the fire development and its effects on human safety, such as ventilation, extinguishing system, time of day etc.

These and some further descriptions necessary to define a design fire quantitatively are specified for the representative spaces below.

3.4.1 Accommodation space fire scenarios

The characteristics of the accommodation space is unique and it therefore represents itself. It is a large public space on deck 2 which has a water mist extinguishment system, detection system as well as two exits towards the ro-ro deck, one to the deck above and one to the fore deck. The compartment is also used as an assembly station and embarkation station. The compartment has several windows and also two doors leading to the engine rooms (via stairways). This space surrounds three WCs, a stairway up to deck 3 and also contains void spaces above the ceiling. Furthermore, the fire hazards providing conditions and characteristics for the fire scenarios in this space group are listed in table 3.3.

Table 3.3. Fire hazards that define fire scenarios in the accommodation space

Fire hazard	***Findings***
Ignition sources	Electrical failure in equipment or cables, fire spread from surrounding areas, arson, human error (smoking, lighter, match etc.)
Initial fuels	Textiles (e.g. surface of seats, curtains and clothes), plastics in electrical equipment, trash/dust, newspapers, magazines, books, tissues, etc.
Secondary fuels	Textiles: Surface of seats and curtains, flammable liquids spilled by passengers such as alcohol, lighter fluid etc., FRP composite underneath protective surface layer, luggage, baggage, upholstered furniture (certified), trash cans
Extension potentials	Void spaces, ro-ro deck, open deck space above, wheelhouse, WCs, fore deck, cleaning cabinet, staircases, engine room, ventilation, fuel tanks, bow thruster spaces and water tanks.
Target locations	Doors: all doors to the accommodation space are generally closed (have automatic closing devices) and only doors to toilets and to open deck (via stairs) are possible to open for passengers. Windows: not possible to open. Combustible products, such as walls, furniture, luggage, ceiling and other secondary fuels (all surfaces have LFS characteristics and upholstered chairs are certified). Quality of FRP composite divisions, no thermal insulation provided. Surfaces, furniture and luggage (all surfaces have LFS characteristics and upholstered chairs are certified Res. A.652(16)). Information (smoking signs could probably be more visible, information given in speakers?). Water mist extinguishment system. Smoke detectors. Portable fire extinguishers (available).
Critical factors	Oxygen supply, heat release rate, structural fire resistance, reaction to fire properties, restriction of ignition sources, evacuation, automatic extinguishment, detectors, manual extinguishment

3.4.2 Engine room fire scenarios

The ship has two identical engine rooms which make up and represent the engine room space group. The engine rooms are equipped with a gas extinguishment system and both smoke and heat detectors. The engine rooms have two exits; one staircase and one enclosed ladder. All composite surfaces in the engine rooms except in the bilge are insulated (FRD-60) and the surfaces have low flame-spread characteristics. Furthermore, the fire hazards providing conditions and characteristics for the fire scenarios in this space group are listed in table 3.4.

Table 3.4. Fire hazards that define fire scenarios in the engine room

Fire hazard	Findings
Ignition sources	Hot surfaces (normally insulated), electrical equipment causing statistic electricity or overheating (generator, lighting, main switchboard, enclosed battery system, heat fan, engine room fan, bearings, etc.), fire spread from surrounding areas, arson (two doors separating from passengers)
Initial fuels	Grease/hydraulic oil, fuel (diesel), cabling, plastic covers/electronics, fuel/oil spray, paper/trash (very limited), rags (very limited)
Secondary fuels	Grease/hydraulic oil pool and spray, fuel (diesel pool and spray), cabling, hoses, clothes, plastic covers, electronics, switchboard, fuse box etc.
Extension potentials	Steering gear (FRD60), void space on deck 1.5 (FRD60), cargo deck (FRD60), water tanks (FRD60), staircase (FRD60)
Target locations	Door closers A60/FRD60 doors, ventilation system routine in case of fire, fire dampers, non-insulated surfaces below insulation (only LFS). FRD60 down to 300 mm below summer waterline, quality of insulation (FRD60), smoke and heat detectors, water mist extinguishment system, portable fire extinguishers, hydrants on cargo deck, insulation of hot surfaces, gas extinguishing system.
Critical factors	Oxygen supply to fire, reaction to fire properties of surface materials, manual extinguishment, automatic extinguishment, detection, fire growth rate, evacuation.

3.4.3 Worst-case auxiliary machinery space fire scenarios

The auxiliary machinery space group include the steering gear rooms (SB and PS) and the bow thruster rooms (SB and PS). The auxiliary machinery spaces are equipped with smoke detectors but not with any automatic extinguishment systems. The representative worst-case auxiliary machinery space has one exit, a ladder to open deck. All surfaces in the space are of unprotected FRP composite (hence not achieving low flame-spread characteristics). Furthermore, the fire hazards providing conditions and characteristics for the fire scenarios in this space group are listed in table 3.4.

Table 3.5. Fire hazards that define fire scenarios in the worst-case auxiliary machinery space

Fire hazard	*Findings*
Ignition sources	Arson (not easily accessible, only by crew since hatch is locked, possible to open from below), human error during inspection and repair (unmanned during operation), electrical failure or overheating (generator, lightning, very limited amount of electrical equipment, mainly lights), static electricity, fire spread from surrounding areas, hot surfaces (normally insulated), mechanical failure or overheating
Initial fuels	Paper/trash (very limited), grease/hydraulic oil pool or spray, cabling, plastic covers/electronics, rags (very limited)
Secondary fuels	Grease/hydraulic oil, structural FRP composite material, cabling (limited amount), tubing (limited amount
Extension potentials	Engine room (insulation in engine room), adjacent void spaces, ro-ro deck, accommodation space
Target locations	Door/hatch (normally closed except in case of inspection, otherwise only an approx. 100 mm diam. ventilation penetration is provided). Surface material, unprotected in base design provides fuel to potential fire without restrictions. Quality of FRP composite divisions. No means for manual extinguishment are provided, e.g. portable extinguishers. Smoke detectors. No automatic fire extinguishment system (e.g. sprinkler system).
Critical factors	Oxygen supply to fire, reaction to fire properties, structural fire resistance, manual extinguishment, detection, automatic extinguishment, possible fire growth rate and heat release.

3.4.4 Worst-case void space fire scenarios

Void spaces are normally closed volumes (no large ventilation openings) and are, of course, never populated. All void spaces on the ship are included in this group (except void spaces above ceiling in accommodation space). They do not have automatic extinguishment system or detection system. The potential for fire development is represented by the worst-case design fire amongst the spaces in this category, i.e. the largest space with the most combustible materials and the largest ventilation openings. Furthermore, the fire hazards providing conditions and characteristics for the fire scenarios in this space group are listed in table 3.6.

Table 3.6. Fire hazards that define fire scenarios in the worst-case void space

Fire hazard	*Findings*
Ignition sources	Electrical failure (e.g. overheating, shortcut), fire spread from surrounding areas
Initial fuels	Dust, trash, grease, oils, cabling etc.
Secondary fuels	Structural FRP composite material, cabling, combustible piping and insulation, plastics in electronics.
Extension potentials	Fuel tank, adjacent void spaces, stairway, water tanks, bow thruster space, accommodation space, ro-ro deck, steering gear, engine rooms
Target locations	Door/hatch (normally closed except in case of inspection, otherwise only an approx. 50 mm diam. ventilation penetration is provided). Surface material, unprotected in base design provides fuel to potential fire without restrictions. Quality of FRP composite divisions. Smoke detectors are not available. No means for manual extinguishment are provided, e.g. portable extinguishers. No automatic fire extinguishment system (e.g. sprinkler system)
Critical factors	Oxygen supply to fire, reaction to fire properties, structural fire resistance, detection, manual extinguishment, automatic extinguishment, possible fire growth rate and heat release.

3.4.5 Wheelhouse fire scenarios

The wheelhouse is also unique on the ship and represents itself. It is equipped with extinguishing system and detection system. The extinguishment system is manually activated in the wheelhouse. The wheelhouse is always populated while at sea and there are more than one exit from the compartment. The wheelhouse has windows and the potential for fire development is represented by the actual conditions in this space. Furthermore, the fire hazards providing conditions and characteristics for the fire scenarios in this space group are listed in table 3.7.

Table 3.7. Fire hazards that define fire scenarios in the wheelhouse

Fire hazard	*Findings*
Ignition sources	Electrical failure in equipment or cables, fire spread from surrounding areas, human error (smoking, lighter, match), pyrotechnical equipment (emergency flares etc.)
Initial fuels	Newspapers, magazines, books, tissues, clothes, textiles (e.g. surface of seats, curtains and clothes), plastics in electrical equipment, trash, dust
Secondary fuels	Upholstered and wood furniture and consoles, FRP composite underneath protective surface layer, suitcase/baggage, binders, books, structural composite material, cables, control panel and plastics in electronics.
Extension potentials	WC, accommodation space, open deck space, exterior surfaces.
Target locations	Space volume (medium sized). Doors: generally closed (have automatic closing devices), none of which are possible to open for passengers. Windows: possible to open and often used for ventilation. Division surfaces, furniture and seats (all surfaces have LFS characteristics and upholstered chairs are certified Res. A.652(16)). Quality of FRP composite divisions, no thermal insulation provided. Smoke detectors available. Water mist system installed. Portable fire extinguishers available.
Critical factors	Oxygen supply, reaction to fire properties, structural fire resistance, detection, automatic extinguishment, manual extinguishment, critical factors, oxygen supply to fire, reaction to fire properties, fire resistance, detection, automatic extinguishment, manual extinguishment, structural fire resistance.

3.4.6 Ro-ro deck fire scenarios

Similarly, the ro-ro deck is unique on the ship and represents its own group. The fire scenarios in this group differs from the other fire scenarios since this they are not enclosed. Oxygen supply to such a fire is unlimited and the fuel load on the cargo deck is potentially very large with cars, trucks and other cargo. Dangerous goods will although not be transported with more than 25 passengers on board. A fire detection system and a manually operated drencher system has been installed on the ro-ro deck in the base design. Furthermore, the fire hazards providing conditions and characteristics for the fire scenarios in this space group are listed in table 3.8.

Table 3.8. Fire hazards that define fire scenarios on the ro-ro deck

Fire hazard	*Findings*
Ignition sources	Human error (smoking etc.), arson, car fire due to any failure, electrical failure, bunkering, fire spread from other areas
Initial fuels	Hydrocarbon fuel, burning car, deck equipment, trash cans, plastics/rubber on deck, lighter fluids
Secondary fuels	Dangerous goods, vehicles (tires, plastic bumpers), composite structural materials, lighter fluid or other flammable liquid or fuel, deck equipment.

Extension potentials	Surrounding exteriors, open deck space on deck above, accommodation space.
Target locations	Impossible to limit ventilation (large open area with unlimited excess to oxygen). Trash cans. Flammable oils. FRP composite surfaces. Surface material, unprotected in base design provides fuel to potential fire without restrictions. Quality of FRP composite divisions, no insulation. Ignition sources, such as engines in vehicles and smoking. Drencher system according to requirements. Portable extinguishers and fire hoses. Flame detectors. Evacuation routes. Surface material, unprotected in base design provides fuel to potential fire without restrictions.
Critical factors	Oxygen supply, amount of initial fuels, amount of secondary fuels, reaction to fire properties, fire resistance, ignition sources, automatic extinguishment, manual extinguishment, detection, evacuation, risk of fire spread to exteriors and particularly under overhang.

3.4.7 Worst-case stairway fire scenarios

Except from the staircase included in the accommodation space, the ship has two kinds of stairways which make up this space group. Both stairways are connected to the engine room. One leads forward from the engine rooms and contains regular stairs. The other one is located in the aft part of the engine rooms and contains a ladder up to ro-ro deck. Both stairways are evacuation routes from the engine rooms and contain detection system but no automatic extinguishment system. The largest stairway with the most potential for combustible materials will be used as representative worst-case stairway for this group. The passengers will not have access to any of the stair cases (for crew only). Furthermore, the fire hazards providing conditions and characteristics for the fire scenarios in this space group are listed in table 3.9.

Table 3.9. Fire hazards that define fire scenarios in the worst-case stairway

Fire hazard	***Findings***
Ignition sources	Electrical failure in equipment or cables, fire spread from surrounding areas, arson, human error (smoking?)
Initial fuels	Cables, dust/trash, wall decorations, garbage bags
Secondary fuels	Ceiling and bulkheads (LFS), furnishing (not allowed), garbage bags (not allowed)
Extension potentials	Engine room, accommodation space, void space, ro-ro deck, engine room, ventilation casings.
Target locations	Doors: all normally closed. Ventilation: sparse natural ventilation from accommodation space. Walls, floors and other surfaces (fulfil low flame-spread characteristics). Quality of FRP composite divisions. Smoke detectors. Water mist extinguishing system.
Critical factors	Oxygen supply to fire, reaction to fire properties, structural fire resistance, manual extinguishment, detection, automatic extinguishment

3.5 Fire spread

The above groups of fire scenarios describe the conditions for a fire starting in the concerned spaces. Note that fire hazards were identified with regards to fire spread, which needs to be taken into account. The accommodation space and particularly the ro-ro deck were recognized to have high probability of fire spread to other spaces via exterior combustible surfaces. The greatest fire risk was reckoned on ro-ro deck, where hydro carbon fires are likely to occur and where dangerous goods may be stowed.

Another fire hazard which was identified when considering fire spread was blockage of the assembly station. If a significant fire is more likely in the accommodation space on the Eco-Island ferry, then it is also more likely that an accommodation space fire cannot be managed (in the base design). An uncontrolled fire in the accommodation space could potentially make the entire embarkation station inaccessible. Such a scenario could lead to catastrophic consequences and should be taken into account in the quantitative analysis, preferably as part of the accommodation space fire. Hence, this could occur also in the prescriptive design but, depending on how risk control measures are directed it could be suitably avoided in the Eco-Island ferry.

3.6 Further specification of fire scenarios

The forthcoming quantitative analysis will contain evaluation of the trial alternative designs using the design fire scenarios. The design fire scenarios will therefore need to be further specified in the quantitative analysis, including:

- specification of factors affecting the fire development, e.g. fire growth rate, amount of fuel, ventilation openings, sprinkler system and size of space.
- development of a heat release rate curve for each design fire from the above information, including fire ignition, established burning, fire growth, fully developed fire, duration and decay.
- development of a timeline for each design, including fire ignition, fire detection, fire alarm, first aid, activation of extinguishing system, fire fighting, etc.
- estimation of smoke production and time to reach untenable conditions as well as evacuation simulations will serve as input when evaluating consequences of the fire.

Performance criteria, i.e. quantitative expressions of the level of fire safety in the reference design, will also be developed in the quantitative analysis. Safety margins have therefore not yet been fully determined, since these must derive from established performance criteria. These may include limits of e.g. smoke obscuration, temperatures, egress time, etc.

4. Trial alternative designs

The base design usually needs additional risk control measures (RCMs) in order to achieve sufficient safety. A combination of risk control measures makes up a risk control option (RCO), which is applied to the base design in order to improve safety. Together with the base design, different RCOs make up trial alternative designs, as illustrated in figure 4.1.

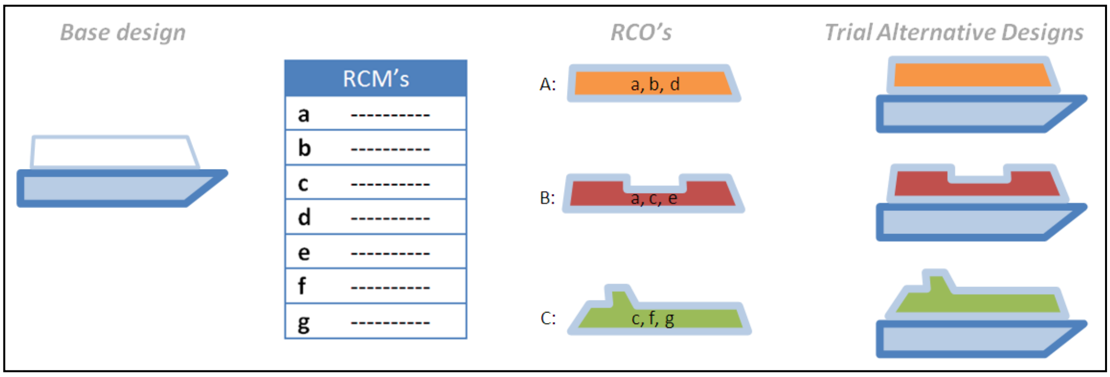

Figure 4.1. Illustration of the base design in relation to trial alternative designs.

A purpose of this report is to specify suitable trial alternative designs, which will be subject to further analysis using the design fire scenarios (see chapter *3. Development of fire scenarios*). In this chapter, the risk control measures are described and trial alternative designs are suggested.

4.1 Risk control measures

The following risk control measures have been identified by the design team as potential measures to reduce the risks of the base design, particularly those caused by deviation from prescriptive requirements.

4.1.1 Redundant fire extinguishment system

In order to increase the probability of a functional extinguishment system, a fully redundant fire extinguishment system can be installed. A correctly designed extinguishment system has proven efficiency against enclosure fires and the extinguishment system itself does not cause any human hazards.

With this risk control measure a redundant water spray system or a water mist system complying with IMO-requirements is installed. The extinguishing systems would be installed with one in each hull. There are although alternatives as to if the whole system should be redundant and in what spaces. The alternatives for system redundancy are to either only have redundant supply units for the extinguishing system or to have full redundancy. Supply unit in this case refers to redundant pumps with full capacity, power supply (including power supply independent of main switchboard) and pressure vessels with the capacity to cover a minimum area of 280 m^2 for 1 minute according to the FSS code [18]. One common piping and nozzle system would be fed from the redundant supply units, placed in each pontoon. Full redundancy would include the redundant supply unit plus fully redundant piping and nozzle system, resulting in two completely redundant extinguishment systems in the concerned spaces. Note that the redundant power supply for sprinkler pumps not only provides 100% redundancy for all emergency electrical systems and functions related to habitable conditions but to all systems on board. Furthermore, the engine room was also considered with a gas extinguishing system for redundancy. Depending on the spaces to be protected, this RCM was divided accordingly:

RCM a1: Redundant supply unit for extinguishing system in stairways, accommodation space (including the void space above the ceiling in the accommodation space if extinguishing system is installed there, see RCM b), wheelhouse and toilets.

RCM a2: Fully redundant extinguishing system in stairways, accommodation space (including the void space above the ceiling in the accommodation space if extinguishing system is installed there, see RCM B), wheelhouse and toilets.

RCM a3: Fully redundant extinguishing systems in engine room. The SB extinguishment system will protect the PS engine room and vice versa.

RCM a4: Redundant supply unit for extinguishing system on ro-ro deck.

RCM a5: Fully redundant extinguishing system on ro-ro deck.

RCM a6: Additional gas extinguishing systems in engine rooms.

4.1.2 Water mist in void space above ceiling in accommodation

Since deck 3 does not fulfil sufficient fire resistance in the base design, the purpose for this RCM is to cool the hot gases in the void space above the ceiling in the accommodation space, in case of an accommodation space fire. Furthermore, if a fire would start in the void space this extinguishment system will control or extinguish such a fire.

This RCM is denominated RCM b.

4.1.3 Drencher on external composite surfaces

The ships drencher system used for protection under the overhangs on ro-ro deck is expanded to cover external composite surfaces. The purpose would be to avoid flame spread and structural damages. This RCM is divided into three RCMs and denominated accordingly:

RCM c1: Drencher system covering the outside of the bulkhead separating the accommodation space from the ro-ro deck.

RCM c2: Drencher system covering the whole ro-ro deck.

RCM c3: Drencher system covering the sides and front of the ship from deck 3 and down. To get reasonable dimensions of the drencher system, the external surfaces would be divided into sections.

4.1.4 Extinguishing system on ro-ro deck with pop-up nozzles

One of the most common origins of a fire on a ro-ro vessel is the ro-ro deck, where ignition sources may be hard control and hydro-carbon fuels are present. Swift extinguishment of a potential fire may be managed with an extinguishing system with pop-up nozzles coming up from the deck.

This RCM is denominated RCM d.

4.1.5 Fog nail for use as a fire fighting tool

The fognail (or fogspear) is a piercing nozzle which allows fire fighters to reach fires into confined spaces. From a technical point, the fognails are very simple. It is a kind of piercing metal nozzle with a specially hardened face. In one end there is a shutoff valve connected to a regular fire hose and from the nail tip a fine water mist is created. It offers the possibility to drive the nail with a hammer through divisions or doors to fight enclosure fires from the outside. The small size of the access hole also minimizes additional oxygen supply to the fire and reduces any risk of flashover or backdraft. The aim with the tool was to reduce the risk to fire fighters and to ensure a speedy and effective use. This fire fighting tool could advantageously be used to reach into spaces which are otherwise not easily accessed in case of fire, such as the many void spaces. In the base design these void spaces have unprotected composite surfaces, implying fuel will always be available. However, the available amount of oxygen is quite restricted since there are no openings to the spaces, except for service hatches and minor ventilation openings for pressure equalization. The most relevant positions for this fire fighting tool would be on deck 2.

This RCM is denominated RCM e.

4.1.6 Cutting extinguisher for use as a fire fighting tool

The cutting extinguisher is a fire extinguishing tool which combines abrasive water jet cutting with water spray extinguishing through a hand-held nozzle. The fire-fighter can approach the fire from outside the fire compartment and then use the cutting action to drill a small hole through a door or wall. Switching to a water spray then allows the fire to be fought, as with a conventional fog nozzle. The main advantages of this system are in increased safety for the fire-fighter, as they may remain outside the most hazardous area. The small size of the access hole also minimizes the additional oxygen supply to the fire and reduces any risk of flashover or backdraft. This fire fighting tool could be relevant on the ship, particularly to reach spaces in order to reach into spaces which are otherwise not easily accessed for fire fighting, mainly found on deck 1 and deck 1.5.

This RCM is denominated RCM f.

4.1.7 Smoke detectors in void spaces

With this RCM the fire detection system is expanded to cover the void spaces. If a fire starts in a void space there is typically a significant amount of available fuel provided by the unprotected combustible FRP composite materials. However, oxygen supply is quite limited.

This RCM is denominated RCM g.

4.1.8 Encapsulated electrical equipment

In order to further reduce the probability of ignition in certain spaces, only encapsulated (IP 44 or better) electrical equipment is used. This RCM is divided into three parts, covering different spaces:

RCM h1: Encapsulated electrical equipment in void spaces on deck 1.

RCM h2: Encapsulated electrical equipment in void spaces on deck 1.5.

RCM h3: Encapsulated electrical equipment in auxiliary machinery spaces.

4.1.9 Surfaces of low flame-spread characteristics

With this RCM surfaces in certain spaces will be made to achieve low flame-spread characteristics according to the FTP Code [15]. This will reduce both the probability of ignition as well as the probability and speed of fire growth. Note that this is a safety measure which is in accordance with prescriptive requirement and thus decreases the posed deviations. This RCM is relevant in a few different places and the RCM was therefore divided accordingly:

RCM i1: Surfaces of low flame-spread characteristics in auxiliary machinery spaces.

RCM i2: Surfaces of low flame-spread characteristics in void spaces on deck 1.

RCM i3: Surfaces of low flame-spread characteristics in voids on deck 1.5.

RCM i4: Low flame-spread characteristics on FRP composite surface facing ro-ro deck on bulkhead between ro-ro deck and accommodation space.

RCM i5: Low flame-spread characteristics on all FRP composite surfaces facing ro-ro deck.

RCM i6: Low flame-spread characteristics on all FRP composite surfaces facing open deck space on deck 3.

RCM i7: Low flame-spread characteristics on all FRP composite surfaces above deck 2.

4.1.10 Fire Resisting Material covering FRP composite surfaces

With this RCM surfaces are covered with a panel or liner complying with Fire Restricting Material requirements in the HSC Code. This will affect the fire and smoke development in the initial stages of a fire. In later stages when the fire has reached a certain size, the covered combustible materials may still contribute to the fire. If improved surface materials are deemed necessary it might not be needed in all spaces in the ship. Hence this RCM is divided into three parts covering different spaces:

RCM j1: FRM in accommodation space.

RCM j2: FRM in toilets.

RCM j3: FRM in stairways.

RCM j4: FRM in auxiliary machinery spaces.

RCM j5: FRM in wheelhouse.

RCM j6: FRM in void spaces.

RCM j7: FRM in cleaning closet.

4.1.11 Improved floor construction

This RCM concerns two areas where non-combustible surfaces could be relevant. In the base design the deck surfaces in the accommodation space and wheelhouse are covered with a 20 mm thick plywood. With this RCM the plywood is replaced with 20 mm thick Rockwool (high density) plates, reducing the amount of combustible material in the accommodation space, covered by a carbon FRP laminate.

This is denominated RCM k.

4.1.12 Non-combustible surfaces on ro-ro deck

This RCM implies making different surfaces on ro-ro deck in non-combustible material. The RCM has therefore been divided in the deck, overhang as well as the bulkhead towards the accommodation space. Making the ro-ro deck surface non-combustible could imply covering the FRP composite with a 5 mm aluminium sheet. Such a surface would not be easily ignited by a small initial fire, e.g. due to a fuel spill. Overhang structures above ro-ro deck are vulnerable and exposed in case of fire. In the base design they are made in FRP composite but this part of the RCM consists in making them in non-combustible material instead (e.g. aluminium or galvanized steel grating). In order to make the outer surface of the bulkhead between ro-ro deck and the accommodation area non-combustible a thin aluminium sheet could be fitted on the surfaces.

RCM l1: Covering the ro-ro deck by a non-combustible surface.

RCM l2: Covering boundary bulkhead towards the accommodation space with a non-combustible surface.

RCM l3: Non-combustible overhangs above ro-ro deck.

4.1.13 Improved FRP composite qualities

This RCM implies adjustments of the FRP composite composition in order to gain better fire resistance in certain exposed places where extra fire resistance is needed to protect from collapse. Primarily substitution of the core material is considered at this stage. The RCM has been divided depending on the concerned spaces and is denominated accordingly.

RCM m1: FRP composite with balsa core in the overhangs above the ro-ro deck.

RCM m2: FRP composite with balsa core in deck 3.

4.1.14 Improved structural fire resistance

The purpose of this RCM is to gain fire integrity as well as structural resistance for the FRP composite divisions on the ship. Particularly those divisions where A-60 requirements apply are relevant for this RCM but also some divisions where A class requirements apply without requirements on thermal insulation. To gain the desired fire protection, thermal insulation is provided sufficiently for the structure to be classified as a FRD-30 or FRD-60 . Relevant doors in the concerned space will also be changed to achieve equal protection. The RCM has been divided depending on the concerned spaces accordingly:

RCM n1: Thermal insulation under deck 3 towards the accommodation space and WCs.

RCM n2: Thermal insulation on the accommodation space side of the boundary bulkhead between the accommodation space and the open deck space on deck 3 (in the staircase).

RCM n3: Thermal insulation on the accommodation space side of the boundary bulkhead between accommodation space and ro-ro deck.

RCM n4: Thermal insulation on the ro-ro deck side of the boundary bulkhead between ro-ro deck and accommodation space. Must be considered along with RCM l2 to provide weather protection, also resulting in a non-combustible surface towards ro-ro deck.

RCM n5: Thermal insulation on the accommodation space side of the boundary bulkhead between accommodation space and fore deck.

RCM n6: Thermal insulation on the wheelhouse side of the boundary bulkhead between wheelhouse and open deck space.

RCM n7: Thermal insulation under the overhang above the ro-ro deck. Must be considered along a weather resistant protection.

RCM n8: Thermal insulation on the accommodation space side of the boundary bulkhead between accommodation space and cleaning cabinet.

RCM n9: Thermal insulation on the cleaning cabinet side of the boundary bulkhead between cleaning cabinet and accommodation space.

RCM n10: Thermal insulation on the fuel tank side of the boundary deck between fuel tank and accommodation space.

RCM n11: Thermal insulation encapsulating fuel tanks (made in steel or equivalent material).

4.1.15 Additional structural divisions

This RCM is meant to structurally subdivide different spaces in order to prevent fire development and fire spread. In the accommodation space this RCM suggests a FRD-60 division is provided as a longitudinal bulkhead, demonstrated by the red line in figure 4.2. Doors with automatic (magnetic) closing devices in the front and aft end of the space would be suitable. An alternative subdivision could be provided as a transversal bulkhead, according to figure 4.2. The subdivision would give the passengers an alternative assembly station in case of a fire in the accommodation space and it will also create two alternative embarkation stations if these are moved suitably. The subdivisions could also be made as B-15 divisions.

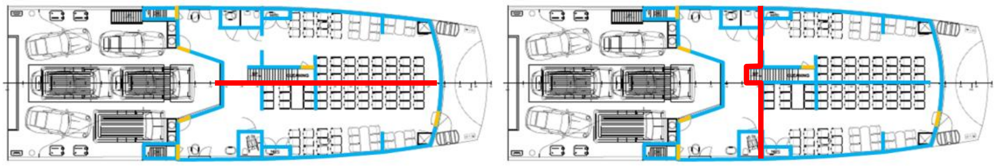

Figure 4.2. Alternative subdivisions of the accommodation space.

The WCs are prescriptively required to be subdivided by B-0 divisions. This RCM also considers such divisions of the WCs. Reg. 9.2.2.3.3 gives possibility to wholly or partly provide the required integrity and insulation of a division by continuous B class ceiling. This RCM therefore also included to make the ceilings in the accommodation space in at least B-0, which provides structural integrity for 30 minutes (the FRP composite provides sufficient thermal insulation). This RCM also entails division of the largest void spaces so that fire cannot prevail. This RCM has hence been divided according to the concerned spaces, denominated accordingly:

RCM o1: FRD-60 division dividing the accommodation space longitudinally.

RCM o2: FRD-60 division dividing the accommodation space transversely.

RCM o3: B-15 division dividing the accommodation space longitudinally.

RCM o4: B-15 division dividing the accommodation space transversely.

RCM o5: B class ceilings in the accommodation space

4.1.16 Door closing devises on WCs

To make sure fire does not spread to or from WCs this RCM suggests to provide door closing devices on WCs.

This RCM is denominated RCM p.

4.1.17 Fire resistant windows

This RCM addresses the risk of fire spread between decks and involves the accommodation space as well as the wheelhouse. The former poses a threat of fire spread to the open deck space and the wheelhouse whilst the wheelhouse itself also could be exposed by a fire on fore deck. The RCM has been divided depending on the concerned spaces and is denominated accordingly.

RCM q1: A-0 windows on the sides of the wheelhouse.

RCM q2: A-0 windows in the wheelhouse.

RCM q3: A-0 windows in the front part of the accommodation space (frame #16 and forward) under the wheelhouse.

RCM q4: A-0 windows in the whole accommodation space.

4.1.18 Alarm on openings to confined spaces

This RCM aims to control whether doors and hatches are open, since oxygen supply may be critical to confined spaces with much combustibles (consisting of unprotected FRP composite surfaces). The door alarm would sound in the wheelhouse and only applies to doors which are normally closed and are not opened due to repair/maintenance. The RCM has been divided depending on the concerned spaces and is denominated accordingly.

RCM r1: Door alarm for WCs. Only considered in combination with RCM p.

RCM r2: Hatch alarm for voids.

RCM r3: Hatch alarm for auxiliary machinery spaces.

4.1.19 Smoking hazard minimization

This RCM means that smoking will not be allowed on the ship and could also entail a number of measures to make sure that this requirement is followed. The RCM has been divided and denominated accordingly:

RCM t1: Clear no smoking signs provided on ro-ro deck, in the accommodation space, on the open deck space, fore deck and in the wheelhouse.

RCM t2: Rounds for crew in accommodation space and open deck space during voyage and notification on ro-ro deck during embarkation, to make sure no one is smoking.

RCM t3: Information TV screens showing that smoking is not allowed, flammable liquids are not allowed to carry in the accommodation space and about the evacuation procedure.

RCM t4: Spoken information through speakers given before each voyage about smoking restrictions, handling of flammable liquids and evacuation routines.

RCM t5: Only use of trash cans designed so that fire cannot survive.

4.1.20 New routines

This RCM implies new routines for different purposes to improved fire safety. The RCM has been divided in several new routines, which are denominated and further described accordingly:

RCM u1: Maximum 25 passengers on board when oil tank truck is transported.

RCM u2: No passengers on board during bunkering.

RCM u3: Redundant manual extinguishing equipment ready during bunkering.

RCM u4: Manual extinguishing equipment brought down to the auxiliary machinery spaces in case of repair (portable extinguisher or hydrant from above).

4.2 Risk control options

Since it is not constructive to eliminate risk control measures or combinations of such, no risk control options are firmly defined at this stage. Any of the identified risk control measures described above could form risk control options, individually or in combination with others. Yet, the most likely risk control measures at this stage are specified below.

All potential trial alternative designs considered at this stage include the following RCMs:

- RCMs a1 and a3: Redundant supply unit for extinguishing system in stairways, accommodation space (including the void space above the ceiling in the accommodation space if extinguishing system is installed there), wheelhouse as well as in the engine rooms

- RCM c1 and c3: Drenchers covering the outside of the bulkhead separating the accommodation space from the ro-ro deck as well as the sides and front of the ship from deck 3 and down.
- RCM e: Fog nail for use as a fire fighting tool, at least available on deck 2.
- RCM g: Smoke detectors in void spaces.
- RCMs h1, h2 and h3: Encapsulated electrical equipment in void spaces and auxiliary machinery spaces.
- RCM k: Improved floor construction in accommodation space and wheelhouse.
- RCM l1: Non-combustible surface covering the ro-ro deck
- RCMs n2, n5 and n6: Improved structural fire resistance to achieve FRD60 on:
    - accommodation space side of the boundary bulkhead between the accommodation space and the open deck space on deck 3 (in the staircase);
    - accommodation space side of the boundary bulkhead between accommodation space and fore deck;
    - wheelhouse side of the boundary bulkhead between wheelhouse and open deck space.
- RCM o1: Additional structural division of FRD60 dividing the accommodation space longitudinally.
- RCM p: Door closing devises on WCs
- RCMs t1, t3 and t4: Smoking forbidden and hazard minimization by clear "no smoking" throughout the ship, TV information screens and spoken information through speakers given before each voyage.
- RCMs u1, u2, u3 and u4: New routines consisting of:
    - maximum 25 passengers on board when oil tank truck is transported;
    - no passengers on board during bunkering;
    - redundant manual extinguishing equipment ready during bunkering; and
    - manual extinguishing equipment brought down to the auxiliary machinery spaces in case of repair (portable extinguisher or hydrant from above).

In addition, a number of combinations of RCMs are primarily considered at this stage, making up the following RCOs:

RCO A

- RCM b: Water mist in void space above ceiling in accommodation; and
- RCM i1: Surfaces of low flame-spread characteristics in auxiliary machinery spaces.

RCO B

- RCM n1: Improved structural fire resistance by application of thermal insulation under deck 3 towards the accommodation space and WCs; and
- RCM i1: Surfaces of low flame-spread characteristics in auxiliary machinery spaces.

RCO C

- RCM b: Water mist in void space above ceiling in accommodation;
- RCMs i2 and i3: Surfaces of low flame-spread characteristics in all void spaces; and
- RCM j4: Fire Resisting Material covering FRP composite surfaces in auxiliary machinery spaces.

RCO D

- RCM n1: Improved structural fire resistance by application of thermal insulation under deck 3 towards the accommodation space and WCs;
- RCMs i2 and i3: Surfaces of low flame-spread characteristics in all void spaces; and
- RCM j4: Fire Resisting Material covering FRP composite surfaces in auxiliary machinery spaces.

All of the above RCMs will enhance safety but note that the RCMs denoted by letter “i” are safety measures which imply direct achievement of prescriptive requirements and thus also decrease the posed deviations.

Applied to the base design, the RCMs certain to be included on the ship in combination with the above specified RCOs form the trial alternative designs. All combinations of RCMs could although be assessed in the quantitative analysis, where the most advantageous risk control options will be further defined and analysed. At this stage, the following RCMs are primarily considered to be added if it proves necessary to further improve safety:

- RCM c2: Drencher system covering the whole ro-ro deck;
- RCM d: Extinguishing system on ro-ro deck with pop-up nozzles;
- RCM i4 or i5: Low flame-spread characteristics on FRP composite surface facing ro-ro deck (on bulkhead between ro-ro deck and accommodation space) or on all FRP composite surfaces facing ro-ro deck;
- RCMs j1, j2, j3, j4 and j7: Fire Resisting Material covering FRP composite surfaces in accommodation space, toilets, stairways, auxiliary machinery spaces, wheelhouse and cleaning closet;
- RCM n3: Improved structural fire resistance by added thermal insulation on the accommodation space side of the boundary bulkhead between accommodation space and ro-ro deck;
- RCM n11: Thermal insulation encapsulating fuel tanks (made in steel or equivalent material);
- RCM q1 or q2: Fire resistant windows on the sides of the wheelhouse or in the whole wheelhouse; and
- RCMs r1, r2 and r3: Alarm on openings to WCs, voids and auxiliary machinery spaces.

5 Conclusions and comments

This report contains the preliminary analysis in qualitative terms, as described by Circular 1002 (MSC/Cric.1002 [6]), for the Eco-Island ferry.

The base design of the Eco-Island ferry is designed with structures in carbon fibre reinforced polymer composite instead of steel. The engine room is fitted with thermal insulation and spaces where people may be on a normal basis have surfaces of low-flame spread characteristics. Doors where A-class requirements apply are made in A-0 standard. The ship fulfils applicable prescriptive requirements regarding the fire safety organization, fire fighting routines, active fire protection systems and equipment.

The prescriptive requirements challenged by the base design primarily concern:

- sufficient thermal insulation is not provided in several places which may allow fire to spread to adjacent spaces.
- structures are not made in non-combustible material and may be deteriorated by fire and collapse;
- escape routes on ro-ro deck are not thermally protected from fire on the decks below;
- ro-ro deck is not protected from fire in the accommodation space or engine room;
- accommodation space is not protected from fire on ro-ro deck; and
- surfaces in auxiliary machinery spaces do not achieve low flame-spread characteristics.

Furthermore, the following significant effects on fire safety are considered:

- exterior surfaces are combustible and unprotected which could provide initial fuel, secondary fuel and extension potentials to a fire;
- many divisions internally have combustible material behind the surface of low flame-spread characteristics, which may affect fire growth as well as smoke generation and toxicity;
- the engine room bottoms are only protected with a surface of low flame spread characteristics;
- alternative evacuation stations are not provided; and
- fire containment is improved in the engine room on account to improved thermal insulation.

Based on a hazard identification workshop carried out by a designated design team, seven different groups of spaces were identified with similar conditions for fire scenarios:

8. Accommodation space
9. Engine rooms
10. Auxiliary machinery spaces
11. Void spaces
12. Wheelhouse
13. Ro-ro deck
14. Stairways

Throughout the processes of the Regulation 17 assessment, several suitable risk control measures were identified. Instead of firmly defining what combinations of these to be further evaluated in the quantitative analysis, it was suggested that all possible combinations could form risk control options. Applied to the base design, the risk control options form the trial alternative designs to be evaluated through the design fire scenarios. Yet, a number of risk control measures likely to be implemented were listed and potential risk control measures defined.

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Appendices

A. The revised approach
B. General arrangements
C. FRP composite panels and fire performance
D. Evaluation of prescriptive requirements and associated functional requirements
E. Additional regulation and fire safety evaluations
F. Data from fire hazard identification
G. Procon list

The revised approach

This appendix presents a method to assess fire safety in maritime FRP composite constructions based on [8].

Isolation at sea has made fire risks a major concern in shipping and this is also the key issue when considering ship structures in FRP composite. The main introduced difference in fire safety is that the material is combustible, as opposed to steel which by definition is non-combustible. The international code regulating safety of life at sea, SOLAS [5], does not allow making load-bearing structures in combustible material, according to prescriptive requirements. However, Regulation 17 came into force 2002 and provided an opening for alternative construction solutions if fire safety can be proven at least equivalent to that of a conventionally built ship. It is thus not an exception but an alternative way to fulfil the fire safety requirements of SOLAS. As part of the LASS-C project [19], a method to assess fire safety when making claim to Regulation 17 was developed which embraces the novelty of FRP composite. It was applied to a FRP composite redesign of the Panamax cruise vessel the Norwegian Gem, as further delineated below, and resulted in a preliminary analysis report documented by SP [20] and submitted to the Swedish Transport Agency for approval in principle.

Method to assess fire safety in FRP composite constructions

For FRP composite to become a viable maritime construction material, effects on fire safety from using the material need to be revealed, additional safety measures may be required and an analysis demonstrating and documenting sufficient fire safety is necessary. In Regulation 17, descriptions are summarized for how such analysis should be carried out and more detailed guidelines are found in MSC/Circ.1002 [6] (referred to as Circular 1002). They stipulate that the analysis (referred to as “Regulation 17 assessment”) should be performed by a design team selected to mirror the complexity of the task. The procedure of the analysis can be described as a two-step deterministic risk assessment using performance-based methods of fire safety engineering to compare the fire safety of the alternative design with the level of fire safety obtained by prescriptive requirements [7].The two major steps to be performed are (1) the preliminary analysis in qualitative terms and (2) the quantitative analysis. In the first step, the design team is to define the scope of the analysis, identify hazards and from these develop design fire scenarios as well as develop trial alternative designs. The different components of the preliminary analysis in qualitative terms are documented in a preliminary analysis report which needs an approval by the design team before it is sent to the Administration for a formal approval. With the Administration’s approval, the preliminary analysis report documents the inputs to the next step of the Regulation 17 assessment, the quantitative analysis. Now the design fire scenarios are quantified and, since there are no explicit criteria for the required level of fire safety, outcomes are compared between the trial alternative designs and a prescriptive design. Accordingly, the prescriptive design is a reference design, complying with all the prescriptive fire safety requirements. The documented level of fire safety of the alternative design is therefore not absolute, but relative to the implicit fire safety of a traditional design, which is likewise a product of the implicit fire safety level in prescriptive regulations. Accounting for uncertainties when comparing fire safety levels, the final documentation of the Regulation 17 assessment should demonstrate whether a safety level equivalent to that of a prescriptive design is achieved by the proposed trial alternative designs.

Regulation 17 was developed to undertake innovative design solutions, typically high atriums and long shopping promenades on cruise vessels, without compromising with fire safety. The regulation is in that sense employed to make safety more attractive, but it can also be used to make fire safety more cost-efficient, i.e. to accomplish the same level of fire safety at a lower cost or to increase fire safety at the same cost. In the present case, all steel divisions have been redesigned in FRP composite. Above all, the material is combustible and the fire integrity will be fundamentally affected, which implies significant effects on fire safety. Making claim to Regulation 17, an evaluation of the alternative fire safety design should be based on Circular 1002, which has been identified as a "plausible worst-case type" type of risk assessment. However, in order to establish whether the fire safety of a design with FRP composite can be regarded at least as safe as prescriptive requirements, it has been judged that the risk assessment needs to be more elaborated than what is outlined in Circular 1002 [7]. It is namely not evident how fire risks in such a novel design should be assessed to adequately display effects on fire safety. For one thing, all fire safety requirements are made up around steel designs, leaving many implicit requirements unwritten. To further complicate the comparison of safety levels, prescriptive requirements have unclear connections with the purpose statements of their regulations and also with the fire safety objectives and functional requirements of the fire safety chapter, which are supposed to define "fire safety" [7]. A Regulation 17 assessment involving FRP composite, as any Regulations 17 assessment, should hence not only comply with what is stipulated in Circular 1002, but must also be of sufficient sophistication to describe the introduced novelty in terms of fire safety.

As part of the LASS-C project, a more elaborated method for the first step of the Regulation 17 assessment was developed, which comprises all the requirements of MSC/Circ.1002 but brings the analysis to a higher level [7]. The main differences introduced by the new approach (marked green in figure A1) are the way verification needs are identified as well as the way these differences in fire safety are collected and rated. Furthermore, since the sophistication of the following quantitative analysis needs to be more elaborated in the present application case, the way fire scenarios are specified is also different. The revised approach is further described subsequently.

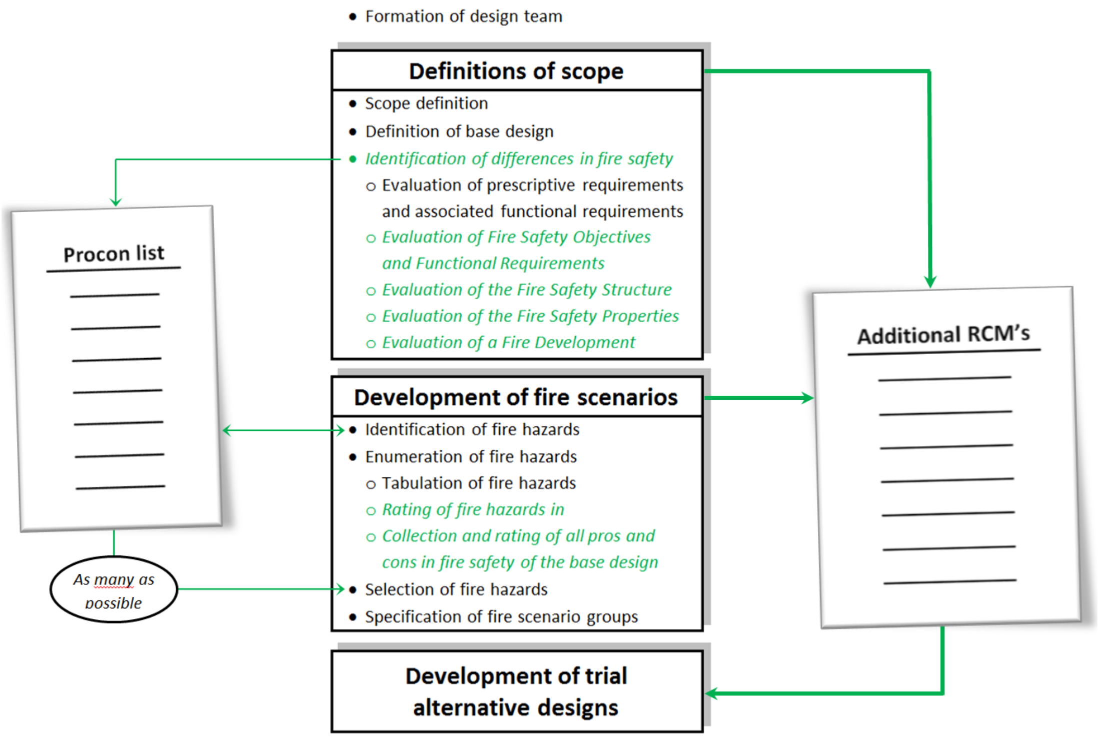


Figure A1. Procedure of the preliminary analysis in qualitative terms, where green represents introduced processes to capture the novelty of FRP composite structures.

Definitions of scope

As described above, the preliminary analysis in qualitative terms can be divided in the three main parts: definitions of scope, development of fire scenarios and development of trial alternative designs. The definitions of scope part consists of three main bullets. Initially, the scope of the current case of alternative fire safety design is simply presented and the regulatory prescribed reference design is defined. Thereafter follow a definition the base design, i.e. the foundational alternative design against which the coming evaluations will be made and to which additional safety measures may be added. In the present case, the scope of the Regulation 17 assessment was the Eco-Island ferry with hull and structural elements designed in FRP composite. This ship works as the base design and the corresponding ship built in steel works as the prescriptive design. Most interiors, fire protection systems and equipment were assumed equal in the two designs, and in agreement with SOLAS requirements. In some places differences the passive fire safety measures were designed differently in the base design, as described above.

The third bullet is key for the following assessment since it is meant to identify the areas of impaired fire safety which need to be regained in an alternative way. However, Circular 1002 only describes to identify deviated prescriptive fire safety requirements and associated functional requirements to identify differences in fires safety. As described above, for a FRP composite design this is not sufficient since all fire safety requirements are made up around steel designs, leaving many implicit requirements unwritten. Furthermore, the fire safety objectives and functional requirements of the fire safety chapter are not fully covered by the regulations purpose statements and these are not fully covered by prescriptive requirements, and vice versa (hence identification of implicit effects on fire safety may be necessary in any Regulation 17 assessment) [7]. Based on the above weaknesses in regulations, it was suggested that the identification of effects on fire safety includes the following additional components when evaluating FRP composite designs (at least until FRP composite in shipbuilding gains more field history and for large scopes of FRP composite designs and deviations):

- evaluation of how fulfilment of fire safety objectives and functional requirements are affected;
- evaluation of how the fire safety structure is affected;
- evaluation of how the fire safety properties are affected; and
- evaluation of how a fire development is affected.

The revised approach thus undertakes the investigation of potential effects on fire safety from a broader perspective.

Development of fire scenarios

In the next part (the development of fire scenarios) there are changes in the suggested approach stemming from weaknesses in the descriptions in Circular 1002, from the above changes and from the required sophistication of the forthcoming quantitative analysis. Firstly a hazard identification is performed where the design team meats in a systematic brainstorming session to thoroughly investigate fire safety in each space of the novel design. At this stage it is important to recognize how the previously identified differences in fire safety will affect the different kinds of fire hazards in the individual spaces. A new logistical process was therefore added to the new approach, where all pros and cons from a fire safety perspective are collected in a “Procon list”. This document works as input to the hazard identification to recognize how the differences in fire safety result in actual fire hazards or improvements and how these work along with other fire hazards at different stages of a fire scenario. Further differences in fire safety which are identified during the development of fire scenarios are also added to the Procon list. In the present application case, fire hazards were identified in a workshops held at Kockums in Malmö with participants from the design team.

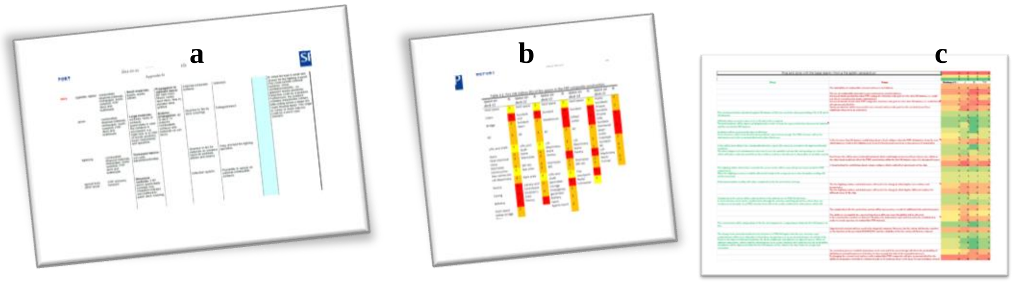


Figure A2. (a) Tabulation of the fire hazards from the hazard identification. (b) Fire hazard ratings of the spaces in the FRP composite construction. (c) A different but more useful enumeration of fire hazards where pros and cons with the base design were rated from a fire safety perspective.

In the hazard identification, fire hazards are naturally organized in different categories, as illustrated in figure A2. This tabulation normally automatically fulfils the stipulation in Circular 1002 to enumerate fire hazards in three different incident categories. The guidelines are although quite vague in this area. What Circular 1002 could be aiming at when stipulating an enumeration into incident classes, and what is more useful, is to rather identify and categorize the plausibly worst fire developments in the spaces, based on the identified fire hazards (illustrated in figure A2). It can be said to constitute some form of fire hazard rating of the concerned spaces, since only plausibly worst consequences are considered and probability thereby is included to a very limited extent. Despite this, and although it is founded on value judgement, this new fire hazard rating provides an indication of the fire risks as perceived by the design team. The fire hazard rating was performed for the involved spaces on the Eco-Island ferry (see table 3.1) and proved useful when selecting fire hazards to form design fires and event trees, which define the fire scenarios. Before the selection, another process was although added, where the collected differences in fire safety in the Procon list were reviewed and rated (see figures A1 and A2). The first priority when selecting fire hazards should be to include as many of those differences in fire safety between the prescriptive design and the base design as possible. Particularly the highly rated differences in fire safety need to be considered in fire scenarios whilst less significant differences alternatively could be managed qualitatively. Thereafter, hazards that significantly will affect the fire development should be taken into account in the fire scenarios. Finally it should be a goal to include as many of the identified hazards as possible and, hence, not only the hazards resulting in the most severe consequences. In the selection process in the present application case, spaces with similar fire hazards are grouped together to cover all the spaces of the alternative design.

The groups of spaces could be said to be represented by a fictitious representative space. In the following fire scenario specification, relevant failure modes affecting a fire development in the representative space are specified along with a plausibly worst-case uncontrolled design fires in that space. Instead of representing all spaces and possible fire scenarios by a few design fire scenarios, the full range of possible fire scenarios can now be quantified for the groups of spaces with similar conditions governing fire development (e.g. potential fire growth, implemented safety measures etc.).

Trial alternative designs

The base design usually needs additional risk control measures (RCM) in order to achieve sufficient safety. A combination of risk control measures makes up a risk control option (RCO) and applied to the base design the RCOs make up trial alternative designs, as illustrated in figure A3. In order to develop suitable trial alternative designs, it is important that the suggested RCMs originate from the identified differences in fire safety and their effects in a fire scenario. It is also during these previous parts that RCMs are generally identified. In the revised approach it is therefore simply suggested that RCMs are collected throughout the assessment and combined to suitable RCOs at the end of the preliminary analysis in qualitative terms. However, new RCMs can be found further on, certain combinations can be missed and their effects on safety are still not evident. Therefore it is not constructive to eliminate risk control measures or combinations of such. Even if particularly suitable RCOs could be suggested, it is therefore advised in the revised approach that trial alternative designs are not firmly defined at this stage.

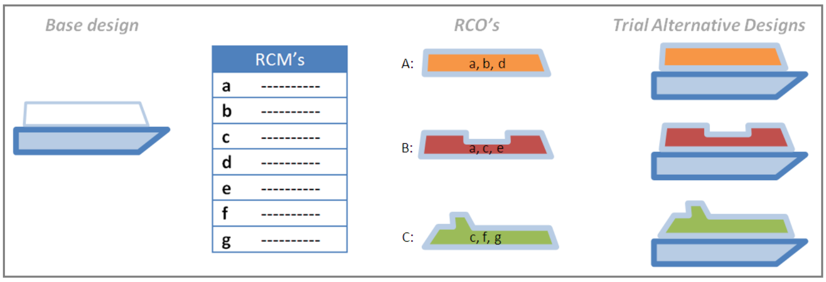
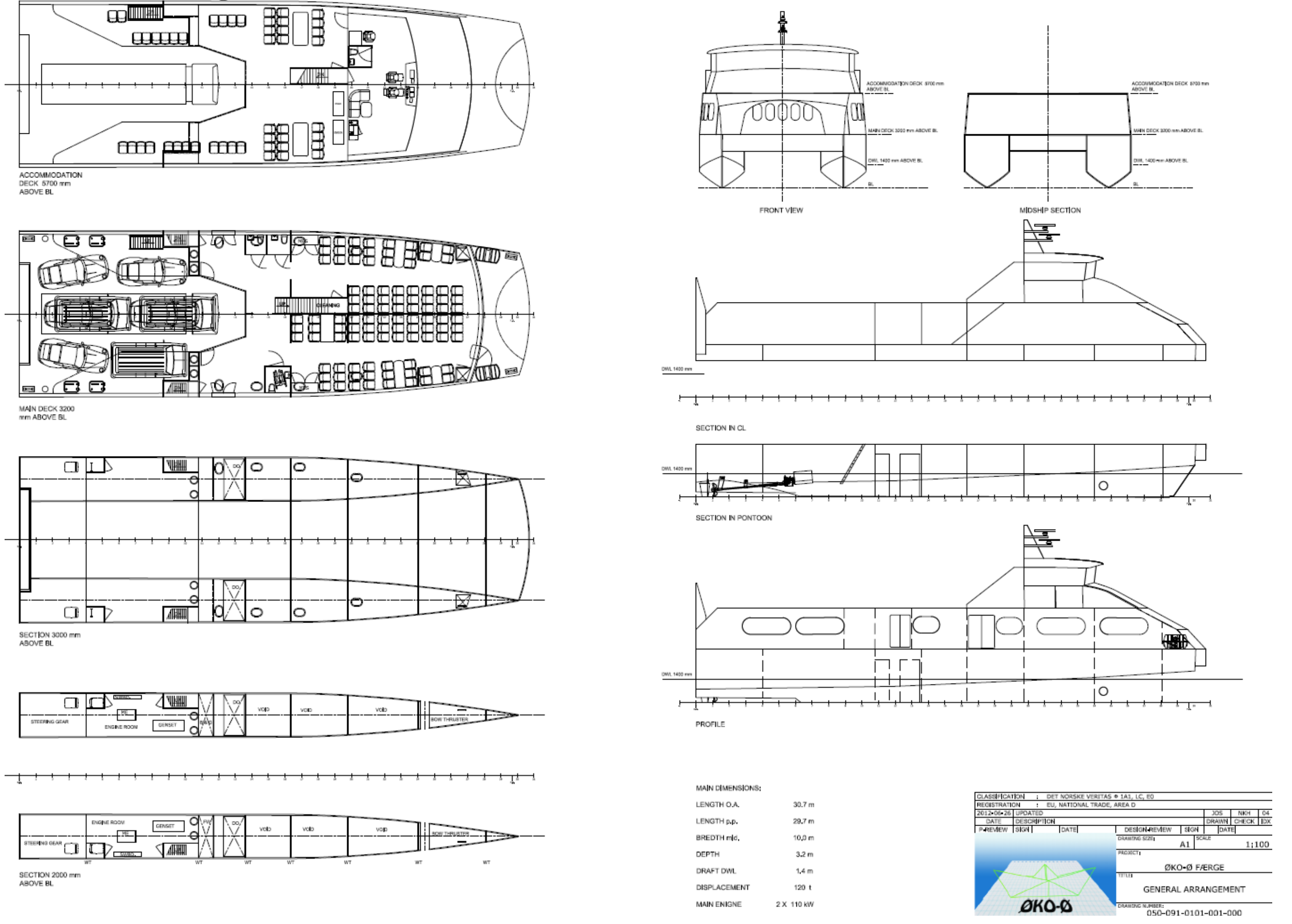


Figure A3. Illustration of the base design in relation to trial alternative designs.

General arrangement



FRP composite panels and fire performance

Steel is a robust ship building material with a high limit for destruction, both when it comes to temperature and loading. Steel divisions generally deteriorate at 400-500^{o}C but permanent deformation as well as fire can spread in great areas when structures are heated to temperatures below those levels. FRP composite matches the rigid and strong qualities of steel and also works as a good thermal barrier [9]. Other benefits with FRP composite are the minimization of maintenance, lack of corrosion, prolonged lifetime, reduced efforts for repairs and, above all, the reduction in weight. However, the material is inevitably combustible and will increase the amount of fuel and the production of toxic smoke if embraced by fire.

Below follow more detailed descriptions of an FRP composite constructions and the keys to its qualities. Thereafter, properties revealed from fire tests are described and weaknesses of tests are discussed.

The structure of an FRP composite panel

An FRP composite panel essentially consists of a lightweight core separating two stiff and strong FRP laminates, which is illustrated in figure C1. The core material generally consists of PVC (polyvinyl chloride) foam or balsa wood and the face sheets are generally made by carbon or glass fibre reinforced polymer. When these laminates are bonded on the core the composition altogether makes up a lightweight construction material with very strong and rigid qualities [2].

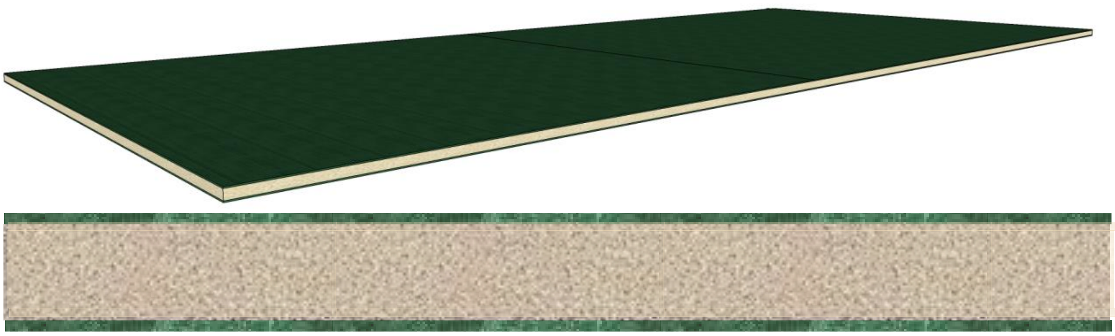


Figure C1. Illustration of an FRP composite panel (top) and a close-up on the lightweight core and the rigid and strong fibre reinforced laminates (bottom).

The key to the prominent properties of the FRP composite is anchored in the separation of the strong laminates. It makes them effective in carrying all in-plane loads and gives ability to withstand high working strains. The separation also provides bending stiffness when exposed to local transverse loading. The core, separating the face sheets, works as a prolate stiffener in the whole structure. It carries local transverse loads as sheer stresses, comparable with how webs of stiffeners behave in stiffened steel panels. The way the material is designed makes it altogether function as a stretched out “I-beam” (see figure C2) and leads to an advantageous distribution of stresses [21, 22].

Figure C2. Illustration of how the lightweight core works as a prolate stiffener in order to provide the FRP composite panel with a distribution of loads similar to an "I-beam".

The performance of FRP composites exposed to fire varies with the composition of core and laminates, mainly depending on the following three conditions:

- thickness of face sheets – a thinner laminate gives a worse performing composite;
- density of core material – a lighter material gives a negative effect on the performance;
- type of plastic – a polymer with lower softening temperature gives less fire resistance.

A typical composite set-up would be a 50 mm PVC foam core (80 kg/m^3) surrounded by two 1.5 mm glass fibre reinforced polymer laminates (approximately 2,100 kg/m^3). The total weight of such FRP-composite would be ~10.5 kg/m^2. This composite could replace a 7 mm steel plate that weighs 55 kg/m^2. Even if the composite requires additional fire insulation or other safety measures the weight-loss is substantial when using FRP composite instead of steel. The strong and rigid characteristics, in conjunction with the weight-effectiveness, makes FRP composite a cost-effective alternative for maritime load-bearing structures.

The FRP composite panel has a low modulus of elasticity, compared to steel. However, due to the "I-beam" type of construction, the panel becomes very stiff. The stiffness, being an extensive property, depends on the amount of material while, on the other hand, the elastic modulus is an intensive property of the constituent material. It allows the FRP composite structure to deform elastically under high working strains and omits reaction forces at interfaces when the hull girder deforms. The ability to deform without stresses in the hull and superstructure is an advantage that eliminates fatigue cracking in deckhouses and reduces maintenance efforts in an FRP composite structure [23].

Insulating qualities

The hull and superstructure of merchant ships are typically made in steel, even if aluminium is also used to some extent. Constructions in steel or aluminium conduct heat very well and will cause a different fire development in comparison with a fire development in a concrete or wood construction. In a metal construction, heat can be conducted far through a ship construction and secondary fires can occur in the most unexpected places if a fire is long-lasting. A shared experience is that there is great probability for fire spread to adjacent spaces if a fire is not controlled within 20-30 minutes, due to the effects from radiation and conduction of heat in traditional ship constructions [24].

Lightweight constructions already have a market in maritime applications, not only when it comes to leisure boats, but also in high speed crafts (HSC). For this purpose, new regulations and standardized tests have been implemented applying to aluminium and composite structures in high speed crafts, the International Code of Safety for High-Speed Crafts [13], also called the HSC Code. The tests for load-bearing structures are equivalent to the standardized tests for steel constructions except for an additional load-bearing requirement. This requirement implies that lightweight decks and bulkheads need to withstand the standard fire test while subject to transverse and in-plane loading, respectively.

For a division made in FRP composite to pass the HSC Code requirements regarding integrity, strength and heat transfer, a certain amount of insulation needs to be attached to the panel. According to requirements, insulation is generally to be applied on the side of the division with the greatest risk of fire. An “A” class steel division is for example generally allowed with insulation only on one side of the bulkhead. However, in structural fire zones in aluminium constructions, where divisions are to be made in steel or equivalent material, the requirements compel to attach insulation on both sides of the bulkhead. Since the strength in aluminium deteriorates at relatively low temperatures it has been required for aluminium divisions to be insulated on both sides in order to be considered as equivalent to steel in structural fire zones [25]. An FRP composite is a good thermal barrier and has demonstrated ability to contain fire on its own [9, 16, 26, 27]. The arrangement with insulation on one or both sides of the structure may still be useful also for FRP composite constructions. Such composition of FRP composite and insulation makes up a Fire Resisting Division (FRD), which has been subject to tests at SP Technical Research Institute of Sweden (see figure C3).

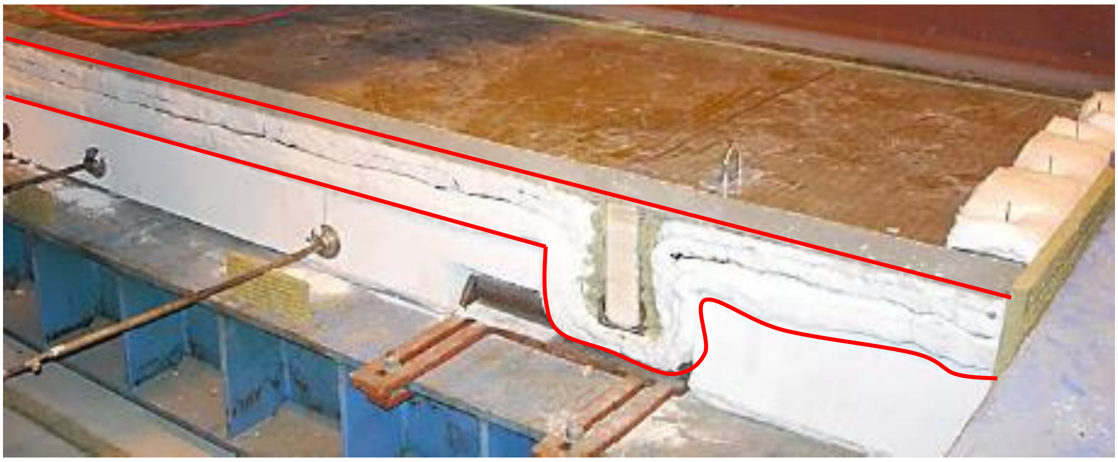


Figure C3. The insulation marked in the picture provides heat integrity to the FRP composite, a composition that makes up a fire resisting division (FRD). An FRD-60 deck construction is here tested on top of a large furnace in accordance with MSC.45(65) [14] in the IMO Fire Test Procedures Code [15].

An FRD deck or bulkhead structure must sustain the specified fire load in a large scale furnace for 30 or 60 minutes in order to be certified as an “FRD-30” or “FRD-60” division, respectively. This kind of division is not to be confused with the currently used light-weight panels, which have no requirements on structural integrity in SOLAS.

Protecting the composite construction from getting involved in the fire for 60 minutes with thermal insulation implies that the temperature on the exposed side of the FRP composite will be kept low enough for the construction to keep its integrity (typically <140˚C when using a PVC foam). It means that the temperature on the unexposed side of the division will be low (35-40˚C when using a PVC-foam) for the full 60 minute period. Thereby the probability for fire spread to the other side is lowered in comparison with steel divisions.

Below follows a summary of some important properties revealed from tests, which are important for the subsequent analyses of the fire safety in the base design.

Properties revealed from fire tests

Throughout the numerous and detailed tests carried out at SP Technical Research Institute of Sweden on FRP composites, the weak link for structural stability of the construction has appeared to be the core material and its bonding to the face sheets. As long as the core is intact and well adhered to both laminates the structural strength of the material is not affected by heat. Therefore the temperature between the core and the face sheet on the side exposed to fire becomes a critical feature. For a low performing FRP composite, with a relatively thin glass fibre reinforced polyester laminate and a PVC foam core, the joint between the first laminate and the core begins to soften at about 100˚C. When the temperature reaches about 130-140˚C the structural performance can be considered deteriorated as the construction becomes deformable. However, if just a part of the material would be exposed to heat, only that limited area would be subject to deformation since FRP composite, unlike steel, does not conduct heat very well.

Before the temperature of the interface between the exposed laminate and the core becomes critical, the strength of the structure will not be affected. However, when the temperature exceeds that level, the load-bearing capacity of the structure will deteriorate quite fast. It is therefore not necessary to test FRD-60 with case specific loading, since its performance in fire tests will not depend on the magnitude of the loading. As explained above, the FRD-60 has therefore been tested with a nominal load, analogous to what is prescribed by the IMO for HSC. Its performance in fire will rather depend on the fire development, i.e. the heat production (temperature) and the time of exposure. When exposing a specimen to a fire specified by the standard temperature-time curve the strength of an FRP composite panel will for that reason mainly depend on the time of exposure [2].

In the 60 minute fire test it is critical that the temperature of the FRP laminate-core interface of the fire exposed side stays below the critical temperature in order for the structural performance to be satisfying throughout the test. The temperature on the unexposed side of a FRD-60 division will, down to its high insulation capacity, therefore be virtually at room temperature even after 60 minutes of fire. Tests confirmed a temperature on the unexposed side of the division of about 45˚C, which can compare to the average 140˚C or peak 180˚C allowed according to the strictest division requirement in SOLAS. Penetrations and other arrangements, such as windows, doors, ducts, cables and other penetrations, for insulated FRP composite panels have also been tested and certified in accordance with MSC.45(65) [14], as shown in figure C4 [2].

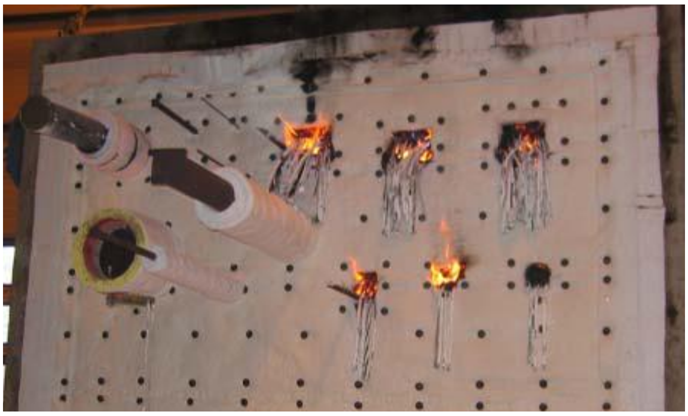


Figure C4. Exposed side of a FRD bulkhead specimen after successful penetration test.

An FRP composite module was tested in full-scale at SP Technical Research in December 2007 [16]. The tests showed that a construction made up by FRD divisions will withstand a fully developed fire for more than 60 minutes without critical damage. A range of tests also investigated different mitigating measures and different fire scenarios.

Uncertainties when using tests to validate FRP composite

Full-scale testing is the method that typically will give the most accurate results of how a design will perform, even if natural variations always will be present. Since it would be very costly to perform all possible scenarios in full scale tests, some chosen scenarios are often tested from which the safety of the rest of the design is evaluated through knowledge of fire dynamics and an engineering approach. This is basically what the prescriptive requirements of SOLAS are founded upon; tests of steel or equivalent materials make out if the construction is valid as a certain division. Numerous performance tests have been carried out on FRP composite to discern whether the novel concept would be valid for different classes of divisions. Apart from the fact that the material is not equivalent to steel in the sense of being combustible, the tests proved for the materials' advantages.

A comparison through tests can although be considered as a quite obtuse way of evaluating the performance of two such diverse materials. When comparing designs through tests there is always a lowest level for passing the test, an acceptance criterion. Obviously the assurance of identical set-ups and measurements is of greatest significance when tests are carried out by different people and stations in several countries throughout the world. However, even without those uncertainties, a test says nothing concerning the performance not represented in the test, e.g. the function if the load, temperature or time in the test increases by 10, 20 or 50 per cent. In general, the prescriptive fire tests of the Fire Test Procedures Code only give pass or no pass. Therefore no information is given on **how** the construction performed during the test or how long it could have performed with satisfaction.

Testing is a good tool for construction comparisons when the main characteristics of the tested materials are similar and a lowest acceptable level of performance is well defined. However, it would be very hard to construct a test that would engage the many different characteristics of steel and FRP composite in a way that all fire risks are represented. Today's fire tests are constructed to measure some key properties reflecting different disadvantages with steel designs and, ideally, representing the performance of steel when exposed to fire. Some characteristics are left out in the tests because of the implicit benefits with the traditional steel solutions. Implicit advantages with steel structures that are not represented in tests are neither possible to evaluate through the tests. Such a property is its ability to withstand high temperatures before deterioration. It is because of the implicit advantages with steel, not visible in tests, that there is an additional requirement for some divisions to be made in non-combustible material. When aluminium was introduced to merchant shipbuilding another advantage of steel needed to be highlighted, its high-performing load-bearing qualities. Therefore aluminium structures need to pass a load-bearing requirement in order to pass structural tests, see [13]. Even if insulated FRP composite passes the structural tests, there is reason to believe that the tests do not fully reflect the risks and benefits with the construction in case of fire. **Hence, implicit properties beyond the tests need to be identified and evaluated.** The fact that FRP composite is combustible is one of the differences that need to be evaluated with a more elaborated approach.

Evaluation of prescriptive requirements and associated functional requirements

In the following paragraphs it is further discussed whether the fire safety regulations of SOLAS are affected by a general change from steel to FRP composite. As illustrated in figure 2.7, each fire safety regulation consists of a purpose statement and prescriptive requirements. The purpose statements have been reproduced for each regulation, followed by comments on how the base design may challenge the regulation. The most important challenges are documented in *2.3 Fire safety regulations affecting the base design*.

Regulation 4 - Probability of ignition

Purpose statement:

The purpose of this regulation is to prevent the ignition of combustible materials or flammable liquids. For this purpose, the following functional requirements shall be met:

.1 means shall be provided to control leaks of flammable liquids;

.2 means shall be provided to limit accumulation of flammable vapours;

.3 the ignitability of combustible materials shall be restricted;

.4 ignition sources shall be restricted;

.5 ignition sources shall be separated from combustible materials and flammable liquids; and

.6 the atmosphere in cargo tanks shall be maintained out of the explosive range.

Comments: Using FRP composite in the overall structure is not in conflict with the regulation objective of this chapter. The prescriptive requirements of this regulation intend to prevent the occurrence of fire by restricting ignition sources and some combustibles. Mainly fuels and the handling of highly flammable materials are concerned, but also a few miscellaneous materials in enclosures. For example, Reg. 4.4.4 concerns primary deck coverings in certain spaces. Otherwise not much is found amongst the prescriptive requirements on how the ignitability of combustible materials should be restricted. Leaving external combustible surfaces unprotected may not be an ignition source, but neither is it in line with the restricting the combustibility, as the functional requirement states. Since external surfaces on ships are typically made up of painted steel there has not been any reason to regulate this matter. This is a great example of where the base design goes beyond the steel-based regulations. The regulation objective and regulation functional requirements can be achieved by excluding unprotected external surfaces or by restricting the their ignitability through risk control measures.

Regulation 5 - Fire growth potential

Purpose statement:

The purpose of this regulation is to limit the fire growth potential in every space of the ship. For this purpose, the following functional requirements shall be met:

.1 means of control for the air supply to the space shall be provided;

.2 means of control for flammable liquids in the space shall be provided; and

.3 the use of combustible materials shall be restricted.

Comments: Neither of the first two functional requirements are affected by the change to FRP composite, but the functional requirement in Reg. 5.1.3 must be taken into concern.

The definition of a non-combustible material is given in Reg. 3.33 in SOLAS and defines it as a material that neither burns nor gives off flammable vapours when heated to 750°C. Vinyl ester, which is used as resin on the Eco-Island ferry, will give rise to pyrolysis gases above 500°C and it could therefore be argued that the amount of combustible material is increased when changing from steel to FRP composite. However, in the engine room, where most fires occur [28], the plastic materials will be protected from fire for 60 minutes by usage of insulation, forming a so called fire resistant division in its boundaries to adjacent spaces. This means that the FRP composite will not add to the fire growth potential of the space within the first hour of fully developed fire. Since the purpose of the regulation is to control the fire **in** spaces, and the FRD-60 construction in no way will increase the fire load in the spaces until the fire is allowed to spread to adjacent spaces after 60 minutes, compliance could be connoted in this case.

Ceilings, grounds and linings in accommodation spaces have a large impact on the spread of fire and have to be of low flame-spread characteristics even if larger parts of the ships are changed to FRP composite. In general, all surfaces in accommodation and service spaces made of combustible material must fulfil requirements of a maximum calorific value of 45 MJ/m^2 and have low flame spread characteristics according to the FTP code. According to SOLAS all materials on surfaces and linings chosen for accommodation and service spaces must fulfil Reg. 5.3.2.2 regarding the maximum calorific value of combustible materials and the requirement of combustible materials given in Reg. 5.3.2.3. Exposed surfaces (walls, ceiling and grounds) in corridors, stairways, accommodation spaces and control rooms in the base design are assumed to fulfil the requirement on low flame-spread characteristics in Reg. 5.3.2.4.

In this sense, the base design will not add to the fire growth potential in interior spaces. If open deck is considered a space though, the unprotected combustible external surfaces could give reason to assert deviation from the regulation functional requirement. Surfaces in the base design that have to be taken into concern in the Regulation 17 assessment are unprotected surfaces of FRP composite externally and in spaces such as voids and the steering gear. However, none of these areas will be high risk zones from a fire perspective as they neither are occupied by persons or contain many ignition sources. Furthermore, the fact that combustible material is found just underneath the surfaces of low-flame spread characteristics in the base design must be addressed.

Regulation 6 - Smoke generation potential and toxicity

Purpose statement:

The purpose of this regulation is to reduce the hazard to life from smoke and toxic products generated during a fire in spaces where persons normally work or live. For this purpose, the quantity of smoke and toxic products released from combustible materials, including surface finishes, during fire shall be limited.

Comments: The amount of combustible material and the amount of released gases will obviously be affected if the total amount of combustible material is increased and a potential protective layer has been consumed. Toxicity may be affected depending on the selection of plastic materials and its arrangement in the space. PVC is for instance known to release HCL and CL_2 during combustion and could be avoided as construction materials in small accommodation spaces if test results from this material show that the amount of gases could be hazardous. The bulkheads in this ship contain Divinycell H which core is made of PVC. The resin on the laminates are made of Vinylester. Hence the regulation objective could be challenged. The regulation objective and Reg. 6.2.1 must be taken into concern.

Regulation 7 - Detection and alarm

Purpose statement:

The purpose of this regulation is to detect a fire in the space of origin and to provide for alarm for safe escape and fire-fighting activity. For this purpose, the following functional requirements shall be met:

.1 fixed fire detection and fire alarm system installations shall be suitable for the nature of the space, fire growth potential and potential generation of smoke and gases;

.2 manually operated call points shall be placed effectively to ensure a readily accessible means of notification; and

.3 fire patrols shall provide an effective means of detecting and locating fires and alerting the navigation bridge and fire teams.

Comments: This regulation is not further discussed as it is fully complied with.

Regulation 8 - Control of smoke spread

Purpose statement:

The purpose of this regulation is to control the spread of smoke in order to minimize the hazard from smoke. For this purpose, means for controlling smoke in atriums, control stations, machinery spaces and concealed spaces shall be provided.

Comments: This regulation is not further discussed as it is fully complied with.

Regulation 9 - Containment of fire

Purpose statement:

The purpose of this regulation is to contain the fire in the space of origin. For this purpose the following requirements shall be met:

.1 the ship shall be divided by thermal and structural boundaries;

.2 thermal insulation boundaries shall have due regard to the fire risk of the space and adjacent spaces; and

.3 the fire integrity of the division shall be maintained at openings and penetrations.

Comments: This regulation prescribes main vertical and horizontal zones and, where necessary, internal bulkheads to be made up by A class divisions. Requirements on fire integrity of internal decks and bulkheads between different categories of spaces of the ship are given in table 9.1 and 9.2 in SOLAS II-2/9. A class standard means that steel or equivalent material should be used (except insulation). Reg. 3.43 defines steel or equivalent material as a non-combustible material which, by itself or down to insulation provided, has structural and integrity properties equivalent to those of steel (as a result of this definition doors, pipes, windows etc. are also generally required to be made in metal when penetrating A class divisions). FRP composite ignites when exposed to fire and must be combined with thermal insulation in order to gain sufficient fire integrity corresponding to A class standard. Tests carried out by SP have demonstrated that the temperature rise at the unexposed side of a FRD-60 will be as low as 45°C after 60 minutes of fire exposure (temperature rise and integrity test in accordance with the standard test for bulkheads and decks, MSC.45(65) [15]). This low conduction of heat will prevent heat from being transferred long distances through the ship structure [7]. However, the low conductivity of an FRD-60 division can also give rise to a faster fire development within the enclosed space. When the insulation (after 60 minutes) or any protective surface layer is deteriorated, the FRP composite will contribute to the fire and could accelerate the fire development if sufficient oxygen is available. Most FRP composite divisions in the base design are not insulated even though such requirements apply (see *2.2.3 Fire protection of the base design*) which deviates from tables 9.1 and 9.2 in SOLAS II-2/9. Furthermore, even if structural and integrity properties in divisions are achieved by thermal insulation, using combustible FRP composite in A divisions and penetrations pose deviations since it is combustible.

In case of an engine room fire, the base design achieves equal structural properties and the added thermal insulation in divisions and penetrations makes it exceed the requirements on integrity by all means. Especially where only A-0 divisions are required and there is no or limited obligation to insulate divisions or to use fire rated penetrations. Thanks to improved thermal insulation the engine room in the base design will contain a fire in its origin better than the reference design. However, it is a deviation that the divisions surrounding the engine room are only protective one way, i.e. if a fire starts in the engine room and not if it starts in the surrounding compartments.

According to Reg. 9.6.6.1 boundary bulkheads and decks facing the cargo deck need to be insulated to A-60 class standard, which is not fulfilled in the base design (the same requirements is found in Reg. 20, where it is further commented). Reg. 9.7 further describes that ventilation ducts have to be of non-combustible material. As the ducts in the base design are made of FRP composite, this prescriptive requirements is also deviated.

Regulation 10 - Fire fighting

Purpose statement:

The purpose of this regulation is to suppress and swiftly extinguish fire in the space of origin. For this purpose the following requirements shall be met:

.1 fixed fire-extinguishing systems shall be installed, having due regard to the fire growth potential of the spaces; and

.2 fire-extinguishing appliances shall be readily available.

Comments: This regulation presents requirements on the active extinguishing systems and other fire extinguishing equipment. The first functional requirement states that the fixed fire extinguishing systems shall have due regard to the growth potential of the space. The fire extinguishing systems and equipment on the Eco-Island ferry will be of at least the same standard as on the Tun island ferry. However, if the fire growth potential would differ it needs to be taken into concern for of the design of the fire extinguishing systems. For instance, vertical fire growth could happen faster on a FRP composite laminate than on a steel surface if the FRP composite is not covered with a protective surface. Furthermore, in the case of an open door to exteriors, it could be useful to fix an additional sprinkler above the door, if the exterior surfaces are made of unprotected FRP composite. Additional sprinklers may also be useful above windows facing the outside of the FRP composite ship structure to prevent fire from an open window to be spread vertically to other decks from the outside. Hence, fire extinguishing systems and appliances should be readily available regardless of the construction material of the ship [7]. Reg. 10.2.1.4.1 states that piping penetrating machinery spaces should be enclosed by a steel casing or insulated to A-60 class standard. All piping penetrating machinery spaces are of such or FRD-60 standard. In the rest of the ship insulated FRP piping will be used in line with Reg. 10.2.1.1, which requires material readily rendered ineffective by heat not to be used unless adequately protected.

Regulation 11 - Structural integrity

Purpose statement:

The purpose of this regulation is to maintain structural integrity of the ship, preventing partial or whole collapse of the ship structures due to strength deterioration by heat. For this purpose, the materials used in the ships' shall ensure that the structural integrity is not degraded due to fire.

Comments: All materials, even steel, will lose their structural strength when exposed to a large fire. Steel loses its structural strength at about 400-600°C [12] and a sandwich FRP composite laminate may lose its bonding between core and laminate, and thereby structural performance, when heated to about 150°C[1] (or a temperature where the bonding between core and laminate starts to soften). This is the reason why thermal insulation, as for instance mineral wool, is fixed to steel, aluminium and FRP composite, to protect the structural performance. The structural integrity in case of fire should not be worse during the first 60 minutes in a FRP composite design with FRD-60 divisions than in a steel design with A-60 divisions if they are all able to pass the standard test for A-60 bulkheads and decks according to MSC.45(65) [15]. According to the definition of A-0 class bulkheads, the average temperature rise at the unexposed side has no restrictions but they must resist 60 minutes fire integrity.

In the Eco-Island ferry the decks and bulkheads are made in FRP composite, in some cases with thermal insulation. Even if the requirement on fire integrity thereby can be complied with, the requirement to make structures in steel or other equivalent material is not fulfilled, as it interprets as non-combustible material. A severe fire could cause the structure to deform when the thermal insulation is no longer enough to keep the temperature sufficiently low. In the worst-case scenario it could bring about a local collapse when the FRP laminates detach from the core. However, the good structural behaviour of the FRP composite in a real fire, even with local delamination occurring in the composite due to high temperature, was documented at SP in a full scale cabin fire test [16]. It is worth remembering that also a steel construction suffers from strength deterioration, and particularly deformation problems, when heated enough.

Regulation 12 - Notification of crew and passengers

Purpose statement:

The purpose of this regulation is to notify crew and passengers of a fire for safe evacuation. For this purpose, a general emergency alarm system and a public address system shall be provided.

Comments: This regulation is not further discussed as it is fully complied with.

Regulation 13 - Means of escape

Purpose statement:

The purpose of this regulation is to provide means of escape so that persons on board can safely and swiftly escape to the lifeboat and liferaft embarkation deck. For this purpose, the following functional requirements shall be met:

.1 safe escape routes shall be provided;

.2 escape routes shall be maintained in a safe condition, clear of obstacles; and

.3 additional aids for escape shall be provided as necessary to ensure accessibility, clear marking, and adequate design for emergency situations.

[1] Tommy Hertzberg, SP Technical Research institute of Sweden, 2011.

Comments: To fulfil the first functional requirement, the structural integrity of for instance bulkheads and decks in assembly stations, corridors and staircases seem necessary to be safe during at least 30-60 minutes of fire. According to Reg. 13.3.1.3 all stairways in accommodation spaces and service spaces shall be of steel frame construction and all stairs in this ferry are designed to fulfil that requirement. Regarding machinery spaces, Reg. 13.4.1 in claims that two ladders should be present for escape from spaces below bulkhead deck or a ladder and an additional steel door which provides access to a safe escape route to the embarkation deck. It has been proposed in this project that a staircase will be provided in addition to the steel ladder down to the engine room to fulfil this regulation. A staircase down to the engine room is also found in the Swedish regulations [29]. The steering gear room has only one escape route and this may be accepted by the Administration as the maximum distance to the door, in this case a hatch, is less than 5 meter (see 13.4.2.3). From a fire safety point of view one escape route could be sufficient as long as the conditions at the car deck are good or if the room is entered while the ship is not in operation. For the ro-ro deck the requirements in 13.5.1 imply that the escape routes on ro-ro deck must be thermally protected from fire on the decks below; in this case by A-0 divisions against the void spaces and by A-60 divisions against the steering gear and the engine room. The separations against steering gear and void spaces do not fulfil these requirements.

Furthermore, from SOLAS III it is apparent that two alternative evacuation stations must be provided. This is not fulfilled by the base design with only one large evacuation station, i.e. the accommodation space. Furthermore, the life rafts on foredeck must be protected from a fire in the accommodation space, which is not achieved in the base design.

Regulation 14 - Operational readiness and maintenance

Purpose statement:

The purpose of this regulation is to maintain and monitor the effectiveness of the fire safety measures the ship is provided with. For this purpose the following functional requirements shall be met:

.1 fire protection systems and fire-fighting systems and appliances shall be maintained ready for use; and

.2 fire protection systems and fire-fighting systems and appliances shall be properly tested and inspected.

Comments: The functional requirements are not affected by changing the structural material from steel to FRP composite. Inspection should also include detection of holes or openings in the FRD-60 divisions that could affect fire resistance.

Regulation 15 - Instructions, on-board training and drills

Purpose statement:

The purpose of this regulation is to mitigate the consequences of fire by means of proper instructions for training and drills of persons on board in correct procedures under emergency conditions. For this purpose, the crew shall have the necessary knowledge and skills to handle fire emergency cases, including passenger care.

Comments: This regulation is not further discussed as it is fully complied with.

Regulation 16 - Operations

Purpose statement:

The purpose of this regulation is to provide information and instructions for proper ship and cargo handling operations in relation to fire safety. For this purpose, the following functional requirements shall be met:

.1 fire safety operational booklets shall be provided on board; and

.2 flammable vapour releases from cargo tank venting shall be controlled.

Comments: This regulation is not further discussed as it is fully complied with.

Regulation 18 - Helicopter facilities

Purpose statement:

The purpose of this regulation is to provide additional measures in order to address the fire safety objectives of this chapter for ships fitted with special facilities for helicopters. For this purpose, the following functional requirements shall be met:

.1 helideck structure shall be adequate to protect the ship from the fire hazards associated with helicopter operations;

.2 fire-fighting appliances shall be provided to adequately protect the ship from the fire hazards associated with helicopter operations;

.3 refuelling and hangar facilities and operations shall provide the necessary measures to protect the ship from the fire hazards associated with helicopter operations; and

.4 operation manuals and training shall be provided.

Comments: This regulation is not commented as it is not relevant for the reference object.

Regulation 19 - Carriage of dangerous goods

Purpose statement:

The purpose of this regulation is to provide additional safety measures in order to address the fire safety objectives of this chapter for ships carrying dangerous goods. For this purpose, the following functional requirements shall be met:

.1 fire protection systems shall be provided to protect the ship from the added fire hazards associated with carriage of dangerous goods;

.2 dangerous goods shall be adequately separated from ignition sources; and

.3 appropriate personnel protective equipment shall be provided for the hazards associated with the carriage of dangerous goods.

Comments: The reference ship is designed to carry both ordinary passenger cars as well as trucks, e.g. garbage trucks and trucks loaded with oil for domestic heating. Garbage trucks will most likely not fall into any category for dangerous goods but heating oil could fall into class 3, flammable liquids, according to the International Maritime Dangerous Goods Code list [30]. Regulation 19 therefore needs to be kept in mind in the Regulation 17 assessment. However, none of the requirements are affected by the change from a steel to FRP composite in the ship structures.

Regulation 20 - Protection of vehicle, special category and ro-ro spaces

Purpose statement:

The purpose of this regulation is to provide additional safety measures in order to address the fire safety objectives of this chapter for ships fitted with vehicle, special *category and ro-ro spaces. For this purpose, the following functional requirements shall be met:*

.1 fire protection systems shall be provided to adequately protect the ship from the fire hazards associated with vehicle, special category and ro-ro spaces;

.2 ignition sources shall be separated from vehicle, special category and ro-ro spaces; and

.3 vehicle, special category and ro-ro spaces shall be adequately ventilated.

Comments: This regulation describes requirements for ventilation, alarm and detection systems, fire extinguishing equipment and structural requirements for spaces with vehicles. In passenger ships carrying more than 36 passengers, the boundary bulkhead or deck to the vehicle space must be A-60. The structural fire protection can although be reduced to A-0 if the adjacent spaces towards the car deck are of category 5, 9 or 10, i.e. open deck spaces, sanitary spaces or machinery spaces of minor fire risk. Except from not fulfilling A class standard the base design does not achieve A-60 towards the engine room, the accommodation space and the overhang (the open deck space above parts of the ro-ro deck).

The fixed detection and alarm systems on the Eco-Island ferry will be as if the ship would have been built in steel. It will furthermore be designed with an approved fixed water-spraying system for the vehicle space and an appropriate drainage system. As on a steel ship, the vehicle deck will be equipped with fire extinguishers, water-fog applicators and portable foam applicator according to prescriptive requirements.

Even if not required from prescriptive requirements, it might prove necessary from the risk assessment to fit the new Eco-Island ferry with additional active fire extinguishing equipment on the outside of the ship superstructure to ensure that fire does not spread from the vehicle space. The later would be used to fulfil RFR 1.

Regulation 21 - Casualty threshold, safe return to port and safe areas

Purpose statement:

The purpose of this regulation is to establish design criteria for a ship´s safe return to port under its own propulsion after casualty that does not exceed the casualty threshold stipulated in paragraph 3 and also provides functional requirements and performance standards for safe areas.

Comments: Passenger ships constructed on or after 1 July 2010 having a length of 120 m or above or having three or more main vertical zones shall comply with this regulation. As our reference ship is less than 120 meters this regulation can be overlooked.

Regulation 22 - Design criteria for systems to remain operational after a fire casualty

Purpose statement:

The purpose of this regulation is to provide design criteria for systems required to remain operational for supporting the orderly evacuation and abandonment of a ship, if the casualty threshold, as defined in regulation 21.3 is exceeded.

Comments: Passenger ships constructed on or after 1 July 2010 having a length of 120 m or above or having three or more main vertical zones shall comply with this regulation. As our reference ship is less than 120 meters this regulation can be overlooked.

Regulation 23 - Safety centre on passenger ships

Purpose statement:

The purpose of this regulation is to provide a space to assist with the management of emergency situations.
Comments: Passenger ships constructed on or after 1 July 2010 shall have a safety centre on board complying with the requirements of this regulation. The Eco-Island ferry will contain a safety centre wherefrom all fire safety systems are available, such as ventilation systems, alarm systems, fire detection and alarm system, fire and emergency pumps etc. However, this is not affected by the new construction material.

Additional regulation and fire safety evaluations

The individual regulations were analysed above. The fire safety objectives and functional requirements are although not fully embodied in the regulations. Therefore, in order to attain the full extent of the fire safety chapter, the change from steel to FRP composite was judged to need further evaluation [7, 8]. Based on the weaknesses in regulations and the novelty and scope of the ship design, effects on fire safety were identified through the following additional components:

- evaluation of how fulfilment of fire safety objectives and functional requirements are affected;
- evaluation of how the fire safety structure is affected;
- evaluation of how the fire safety properties are affected; and
- evaluation of how a fire development is affected.

The above evaluations may not be necessary as FRP composite in shipbuilding gains more field history and for smaller scopes of FRP composite designs and deviations. Descriptions of the evaluations and their results are presented below.

Fire safety objectives and functional requirements

The fire safety objectives and functional requirements in SOLAS II-2/2 highlight the purpose of the whole fire safety chapter in SOLAS. They are thereby the framework for the following regulations, each with its own purpose statement. From Circular 1002 [6] it can be interpreted that only these purpose statements should be used as functional requirements for an alternative design and arrangements. However, since this is unclear and due to the high degree of innovation in the base design, also the fire safety objectives and functional requirements were evaluated.

Many of the fire safety objectives are clearly represented in functional requirements and prescriptive requirements but others are not as evident. The effects on fire safety will therefore be evaluated through a consideration of how the base design challenges the fire safety objectives and functional requirements, respectively. It also needs to be clear if the design changes will affect a few or several of these, since this will influence the needs for verification.

Fire safety objectives

Using FRP composite instead of steel in deck and bulkhead structures will inevitably affect some of the fire safety objectives. Comments concerning each fire safety objective are summarized in table E1and discussed below.

Table E1. A summary of the fire safety objectives in SOLAS II-2/2.1 and comments on how they are challenged by the base design

The fire safety objectives in SOLAS II-2/2	*Comment on compliance*
.1 prevent the occurrence of fire and explosion;	Generally complied with in the same way as in a prescriptive design.
.2 reduce the risk to life caused by fire;	This objective will be affected, the question is how, which is to be analyzed and verified by the quantitative analysis.
.3 reduce the risk of damage caused by fire to the ship, its cargo and the environment;	On a passenger ship the risk to life is the most significant, even if other values may be of interest to evaluate further.
.4 contain, control and suppress fire and explosion in the compartment of origin; and	Generally the active systems are as required. Many divisions although miss sufficient thermal insulation and are made up by combustible material, which will affect the possibilities to contain and control a fire.
.5 provide adequate and readily accessible means of escape for passengers and crew.	The base design will imply improved conditions for escape within the first 60 minutes.

The use of spaces and its related activities and interiors will be governed by prescriptive requirements. As a result, there will generally not be any differences in the ship designs affecting the first objective. However, it depends on how occurrence of fire is defined, i.e. if it is merely defined as a source of fire or as a fire becoming uncontrolled. The former will not be worse on the Eco-Island ferry but the latter may be affected since more fuels are exist and are left unprotected.

The greatest needs for verification tend to appear in the second and third fire safety objectives (see table E1). These objectives insist on reducing the risk to life, property and environment. Whilst acceptance criteria for risk to property are typically set by shipping companies, criteria for the environment should be set by authorities. A prescribed reduction in risk of damage to the environment is although not clearly presented in the fire safety regulations of SOLAS. Even though the risks to environment and property will definitely be affected by the novel design to some extent, this is outside the scope of this report and is evaluated in a separate life-cycle assessment. The value of hundreds of lives will although always be greater than the cost of a ship or the environmental effects from a ship catastrophe. The greatest risk caused by fire on a passenger ship is therefore the risk of life, which needs to be further evaluated. The second objective does not only mean that passengers and crew should be protected, e.g. by preventing the construction from collapsing during escape. The objective also implies that the construction should be protected from collapse for a certain period after flashover in order to allow for safe fire fighting. There are few requirements on safety for fire fighters (e.g. Reg. 5.2.2.5 and Reg. 8.3.4) but the change from steel to insulated FRP composite will certainly imply some changes which are not represented in prescriptive requirements. This matter therefore needs to be further analysed.

The fourth fire safety objective insists on containing, controlling and suppressing a fire in the space of origin. This objective will generally not be achieved as well by the base design as by a prescriptive design since many divisions lack required thermal insulation and are made up by combustible materials. The base design could, however, also contain improvements which could be beneficial to verify, e.g. from the well-insulated engine room.

The fifth fire safety objective covers escape, which generally is defined as the transportation from a fire to the assembly station, i.e. not to confuse with the evacuation which also includes embarking and launching life safety appliances, or transferring passengers to shore or another ship. Surfaces in some spaces are not of low flame-spread characteristics and some have combustible material (FRP composite) just beneath such protective layer. The escape situation may thereby e.g. be affected by a faster fire growth. It may also be affected by the lack of a second assembly station.

The above effects on the fire safety objectives from implementing FRP composite particularly implies that the safety of human life needs to be verified. Risks to life caused by fire can be evaluated through a risk assessment which will also include some of the other affected fire safety objectives implicitly meant to reduce the risk to life. However, also the effects on property and environment should be assessed, even if left out of the scope of the present study.

Functional requirements

In order to achieve the fire safety objectives set out in table E1, the functional requirements in table E2 have been embodied in the regulations of SOLAS II-2. The change from steel to FRP composite will be viewed through the functional requirements in order to identify relevant differences and needs for verification. Comments concerning each functional requirement are summarized in table E2 and discussed below.

Table E2. A summary of the functional requirements in SOLAS II-2/2.2 and comments on how they are affected by the base design

The functional requirements in SOLAS II-2/2	*Comment on compliance*
.1 division of the ship into main vertical and horizontal zones by thermal and structural boundaries;	The ship is too small to subdivide in such zones but differences in behaviour between FRP composite and steel divisions still need to be established.
.2 separation of accommodation spaces from the remainder of the ship by thermal and structural boundaries;	The effects from separating spaces in the base design by FRP composite divisions need to be established since the divisions are combustible.
.3 restricted use of combustible materials;	Combustible materials will be added but not without restriction and as a general rule not unprotected in spaces occupied by people.
.4 detection of any fire in the zone of origin;	The base design will not affect fulfilment of this requirement.
.5 containment and extinction of any fire in the space of origin;	If using insulation the FRP composite could contain a fire better and thereby promote self-extinguishment. In most cases fire integrity and resistance have although been decreased.
.6 protection of means of escape and access for fire fighting;	The protection of escape routes and access for fire fighting will be affected to some extent.
.7 ready availability of fire-extinguishing appliances; and	The base design will not affect fulfilment of this requirement.
.8 minimization of possibility of ignition of flammable cargo vapour.	The base design will not affect fulfilment of this requirement.

The review of SOLAS II-2/2.2 enlightened some areas that will be affected by a change from steel to FRP composite in the ship structures. The first and the second functional requirements concern the division of a ship and the separation of spaces. Differences in behaviour between boundaries in steel and FRP composite will affect these regulations and are therefore necessary to identify. Regarding the first functional requirement the ship is too small to fall under to corresponding prescriptive requirement in Reg. 9, but there may still be a need for fire zones on the ship, e.g. to provide for safe evacuation. Differences in behaviour between FRP composite and steel divisions need to be established in order to discern the effects on this requirement. When it comes to the second functional requirement, the FRP composite divisions in the base design work as excellent thermal and structural boundaries. However, in case of fire the base design does not achieve this requirement as well as a prescriptive design since the material is combustible and may deteriorate. The effects from separating spaces by FRP composite divisions therefore need to be established.

The third functional requirement makes the usage of combustible materials topical. It invokes an evaluation of the effects from using combustible materials beyond what is permitted in and implied by prescriptive requirements. As a general rule there should not be any unprotected combustible materials added in spaces occupied by people. However, the effects from having external combustible FRP composite surfaces, potentially with some safety measure, need to be verified. The same goes for the effects from having insulated FRP composite in the ship structures.

Functional requirements five and six will be affected in similar ways as the first and second. Depending on the properties of the FRP composite material there will be effects when it comes to containment and extinction of the fire as well as the protection from and access to the fire. If using insulation on the FRP composite panels the improved thermal insulation capacity implies the containment of fire may be affected in a positive way. Except from the ability to contain a fire better and thereby promote self-extinguishment, the base design will not better extinct a fire. In most cases the fire integrity of divisions has although been worsened by decreasing the thermal insulation and fire resistance. The protection of escape routes and access for fire fighting will be affected to some extent. Mainly from making the structures in FRP composite but also since redundant assembly stations are not available. These and the above effects on functional requirements indicate some important needs for verification that ought to be targeted when evaluating the ship design.

Fire safety structure

The analysis in this section utilizes a methodology presented by [31], endorsing an investigation of the goals of different fire safety functions, with consideration to the structure of fire protection as a whole. The goal is to identify the effects on fire safety and the scope of changes in fire protection when implementing a novel design or arrangements. The investigation is a process which begins with a division of the SOLAS II-2 regulations into different fire protection categories. Thereafter follows some relevant theory and an estimation of how a change from steel to FRP composite will affect the fire protection strategy. An interpretation of the changes in the fire protection strategy based on the theory follows subsequently. The result from the investigation is, however, not only the interpretation of the analysis but the whole process giving perspective to the changes.

Different types of fire protection

Depending on the deviations from prescriptive requirements, different parts of the fire protection strategy will be affected. Prescriptive requirements impose a certain design or properties and lead to physical fire protection in the shape of detectors, alarms and sprinkler systems etc. They can also imply restrictions in size, number of people and usage allowed in a compartment. The question is what kind of fire risks a certain requirement was meant to minimize and how? What were the intentions with implementing one or a number of risk control measures [31]?

A synoptic classification of different forms of fire protection was carried out by [32] and implies the following three categories:

- source, i.e. preventing fire;
- exposure, i.e. limiting the development and spread of fire and smoke;
- effect, i.e. preventing and limiting the damage on endpoints.

With this perspective, risk control measures are meant to prevent or limit the occurrence of fire, the spread of fire and smoke or the damage on endpoints (load bearing structures, people on the ship, cargo, environment, neighbouring ships etc.). Each risk control measure can reach one or more of these functions or will give an effect only in conjunction with other measures. A sprinkler system is an example of a system that provides fire protection in more than one way. Except extinguishing the fire and limiting its abilities to spread it can decrease the temperature in the smoke layer, which reduces the thermal effect on load bearing structures [31]. The three categories of fire protection almost represent how SOLAS II-2 is divided into Part B – Prevention of fire and explosion, Part C – Suppression of fire and Part D – Escape. There are, however, some differences. In order to get a better overview of the fire protection strategy in SOLAS II-2 the three categories of fire protection worked as basis for a slightly different division of the regulations:

Source
Regulation 4 - Probability of ignition
Regulation 16 - Operations
Exposure
Regulation 5 - Fire growth potential
Regulation 6 - Smoke generation potential and toxicity
Regulation 7 - Detection and alarm
Regulation 8 - Control of smoke spread
Regulation 9 - Containment of fire
Regulation 10 - Fire fighting
Regulation 14 - Operational readiness and maintenance
Effect
Regulation 11 - Structural integrity
Regulation 12 - Notification of crew and passengers
Regulation 13 - Means of escape
Regulation 15 - Instructions, on-board training and drills

The division is omits Regulation 17 and Part G: Special requirements. From the above division one can tell a certain focus on managing the fire development. This is probably due to the fact that every fire starts small and if it is (1) detected at an early stage, (2) not given the fuel to develop or (3) contained in the space of origin, then there is a great probability it will stay small. To get early control over a fire and limit its potential to grow are two crucial factors to limit the possible consequences of a fire. It is also mainly during this time that people can be present since the risk of inhaling toxic products or getting lost in the smoke while escaping could be hazardous. That is probably the reasons to the focus in SOLAS chapter II-2 on the first stages of a fire.

Multi-purpose complexities

The level of fire safety composed in the prescriptive requirements is based on a network of protection chains made up of numerous risk control measures. A protection chain consists in a number of functions provided by risk control measures (RCM) targeting the source, exposure and effect for a certain endpoint in order to reduce or prevent its risks (see figure E1).

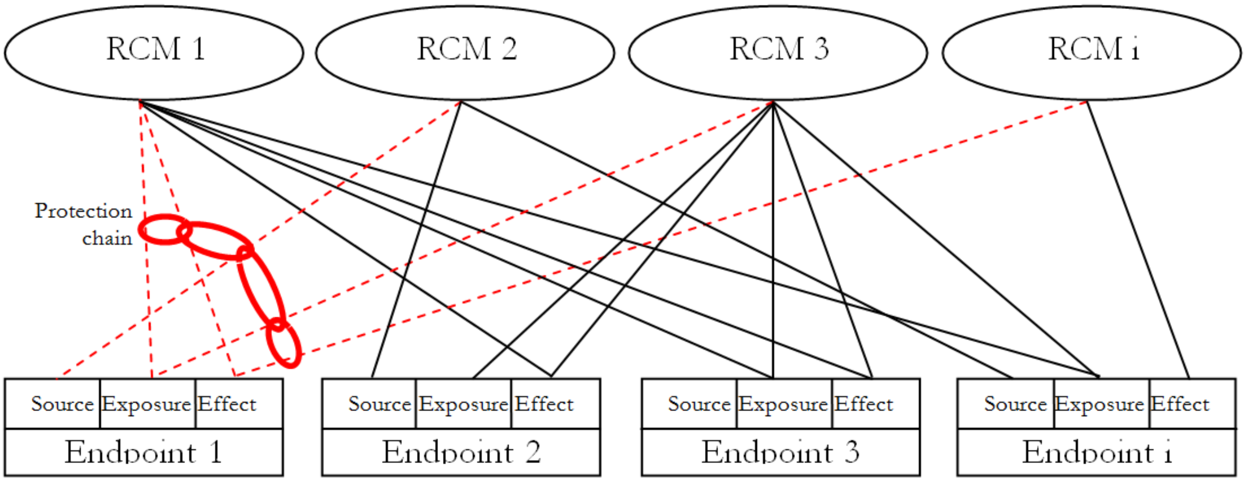


Figure E1. A simplified illustration of how risk control measures (RCM) make up protection chains for a certain endpoint.

The ellipse shaped objects in figure E1 represent risk control measures (e.g. sprinkler system, fire detector or structural division) and the boxes below symbolize endpoints and different categories of how they can be affected by a fire. RCM 3 could for example be structural divisions, preventing fire spread between compartments. Endpoints 2 and 3 could then represent fire fighting crew and property, respectively, since structural divisions limit the exposure and effect on fire fighting crew and the ship itself. All the RCMs connecting with the protection categories of a certain endpoint make up a protection chain. RCMs can have many targets and the connections with endpoints make up a network of protection chains, representing the fire protection strategy. The strategy can be hard to grasp since many of the risk control measures are integrated, i.e. target more than one endpoint. RCM 2, for example, prevents a certain fire source that implies risks to Endpoint 1, Endpoint 2 and Endpoint i (see figure E1). If it was to be exchanged with RCM i it would mean that effects would be mitigated for Endpoint 1 and Endpoint i, but not for Endpoint 2. It is therefore important to identify all intended endpoints, and the aspired protection strategy, when a change is on the table.

It is seldom possible to obtain the intended safety level by implementing risk control measures only targeting one of the three fire protection categories. If it was possible to eliminate all fire sources this would definitely be the best way to minimize fire risks. Fire safety on ships is therefore also to a large extent about how to avoid accidents [33]. However, since it is not possible to fully prevent fire, the exposure category needs to be addressed, e.g. by implementing a sprinkler system as an RCM. A sprinkler system will although not put out a fire with 100 % reliability and it is therefore necessary to also target the possible effects from a fire, e.g. by providing means of escape. In the same way as it is unfavourable to focus only on one fire protection category, it is not beneficial to reduce the number of connections targeting a certain fire protection category. It could be tempting to increase the capacity of one risk control measure, e.g. an RCM targeting the effect from fire, in order to eliminate another RCM. That would, however, reduce the redundancy of the system and it is also often more expensive to reach the same level of safety with one measure than with several [31]. Implementing risk control measures targeting several endpoints or fire protection strategies will help increase redundancy and will decrease the sensitivity of a system. Building protection chains with integrated risk control measures will also imply a more efficient use of resources. However, the complexity grows with the increasing number of connections, which makes it hard for a designer to discern the intrinsic safety level of a system. It is although necessary to comprehend the network of protection chains when implementing novel technology in order to advocate the most suitable risk control measures [31].

Matrix describing universal effects

When modifying fire safety arrangements it is important to be aware of how the protection chains in prescriptive requirements will be affected. A matrix was therefore created, based on a division of the regulations in SOLAS II-2 depending on the fire protection category (see table E3). The matrix will help to identify the protection chains affected by a modification; in the present study a change from steel to FRP composite. It can also be of assistance when taking in the overall effects on fire safety if adapting supplementary arrangements. The matrix is one of the tools employed to assess the effects on fire safety from implementing FRP composite in maritime structures.

Table E3. Matrix describing the overall effects to the fire protection strategy when implementing novel fire safety arrangements, adapted from [31]. The markings symbolize possibly affected functions in the fire protection strategy when exchanging steel (Fe) with FRP composite (FRP)

	Regulation in SOLAS II-2		Change						
			Fe → FRP	Reduction			Supplement		
				R1	R2	R3	S1	S2	S3
Source	4	Probability of ignition	0						
	16	Operations	0						
Exposure	5	Fire growth potential	X						
	6	Smoke generation potential and toxicity	x						
	7	Detection and alarm	0						
	8	Control of smoke spread	0						
	9	Containment of fire	X						
	10	Fire fighting	x						
	14	Operational readiness and maintenance	x						
Effect	11	Structural integrity	X						
	12	Notification of crew and passengers	0						
	13	Means of escape	X						
	15	Instructions, on-board training and drills	0						

A description of how the matrix should be used and interpreted could be useful before the markings are explained. The matrix is meant to help identify and evaluate how different fire safety strategies will be affected when exchanging risk control measures. The functions of the risk control measure intended for removal are marked in the table with minus signs. The same thing is done for the risk control measures planned to be implemented, but the functions are marked with plus signs. By handling each function separately (horizontally) it can be discerned if additional risk control measures need to be supplemented in order to accomplish the same protection. If, for example, the number of minus and plus signs are unbalanced it indicates the protection is more or less centralized (relies on fewer risk control measures). It will affect redundancy and imply an increased need for verification. The same goes for the minus and plus signs in the vertical direction. A balance of minus and plus signs will, however, not imply the same level of safety has been achieved. If the markings are spread vertically it indicates a fire protection function has been replaced by protection of a different category. It means some of the protection chains have been modified which also increases the requirements on verification. If, however, a change implies reduction and supplement only within one fire protection category there could be a possibility that the needs for verification are minor. An evaluation of safety functions is although always necessary [31].

Marking changes in the matrix

In this study the change from steel to FRP composite is to be evaluated in terms of fire safety. It is a quite large exchange of risk control measures but the matrix can reveal some interesting information from even a general use of the matrix. For the purpose of evaluating a design with FRP composite in relation to a steel design, an additional column was added to the matrix. Markings in this column show how functions (regulations) in the fire protection strategy may be affected by a change from steel (Fe) to FRP composite (FRP). Below follow explanations to the markings in the added column.

Section *2.3 Fire safety regulations affecting the base design* made a number of fire safety functions topical. Some of them were Regulations 9, 11 and 13 which are marked with a capital “X” in the matrix, implying the functions will definitely be affected. Regulation 9, placed under “exposure” in the fire protection strategy, is one of the functions which will both positively and negatively affected. The increased thermal insulating capacity in places where FRD-60 is used implies less heat will be conducted through divisions than through a steel division. This would delay propagation of fire and better isolate the fire in the space of origin, which is what the regulation is about. Many divisions will although have reduced fire integrity. Regulation 11 and Regulation 13 represent functions placed under “effect” in the fire protection strategy. Local collapse will be more likely to occur in the base design but the insulating capacity could improve conditions in adjacent spaces. Furthermore, there is no secondary assembly station. There will be certain differences in the fire protection strategy but the total effects need to be further establish.

Regulation 5 is also marked with a capital “X” in table E3. The regulation is placed under “exposure” in the fire protection strategy and, considering the unprotected external surfaces, this function will clearly be affected. The external surfaces will probably be subject to supplementary mitigation efforts, which could be marked in the matrix when established. An outdoor fire would, however, make smoke production less significant (Regulation 6). Leaving out external surfaces there the combustible FRP composite just beneath the surface of low flame-spread characteristics in many places imply a negative change. The smoke production could therefore also be affected, hence the lower-case “x” (representing functions with possibly minor effects due to a change to FRP composite) by Regulation 6. There are although no reasons to believe that smoke spread would behave differently. This and other functions in the fire protection strategy without any relevant effects are marked therefore with “0”.

Regulation 10 and Regulation 14, under ‘exposure’ in the fire protection strategy, have also been denoted with lower-case “x” in the matrix. The reason for this is the need for special training for fire fighting and maintenance in the novel structure. When carrying out work on board, personnel need to know how to renovate with sufficient fire protection afterwards. Strict routines for maintenance and control need to be established in order to avoid exposure of naked FRP composite panels. This issue, on the other hand, needs to be brought up in management systems also for steel. When it comes to fire fighting there will be no need for boundary cooling when fire occurs in compartments with FRP composite boundaries and particularly for FRD-60 divisions. This effect could relieve some of the crew to assist with the evacuation instead. Another difference when fighting fires in composite compartments is that it can be carried out without actually entering the fire enclosure. The gear for such operations is considered standard equipment for fire fighting in composite structures. It is obviously more effective for fires in small spaces whilst regular routines are more practicable in larger spaces. Moreover, fire fighters need to further consider the risk of local collapse.

Using the matrix to analyse a change to FRP composite

The markings in the matrix are now to be interpreted. Since the indications are only made to recognize changes, there is obviously nothing to be made out of the horizontal balance of signs. Whether the effects on the marked functions in the fire protection strategy are positive or negative needs to be further analysed which, however, also is a result. When the effects on functions have been made clear, supplementary risk control measures can be implemented to mitigate risks to the relevant functions. Looking at the markings from a vertical point of view there are no indications on effects on ignition sources. The markings are, however, widely spread in the “exposure” and “effect” categories of the fire protection strategy. It indicates many different parts of the strategy will be affected by a change to FRP composite, which increases the needs for verification. Seven out of eleven functions will possibly be affected by the change, meaning many of the protection chains will be modified. This is also a reason for a thorough verification in order to establish all effects on fire safety. When the effects have been recognized and estimated, the matrix can help find suitable supplementary actions.

Using the matrix helps identify and evaluate how different fire safety strategies are affected but it is also important to evaluate the intrinsic effects on fire safety. Can for example an increase in capacity for a risk control measure targeting the effects to an endpoint replace a measure targeting the exposure, or are there other perspectives to consider. This will be evaluated by investigating fire safety properties and how different functions interrelate.

Fire safety properties

When evaluating changes in safety systems it is typically done by comparing the affected functions, e.g. how changes will have an effect on conditions for evacuation. Safety systems can, however, also be described by different properties revealing their overall performance [34]. For example, the distance in escape routes, quality of linings and insulation for load-bearing structures cannot be reduced and complemented only by installing a sprinkler system intended to extinguish a possible fire. The achieved safety will not be the same, e.g. since it is not enough only comparing systems when they are working. Active systems generally have lower reliability than passive systems, which needs to be accounted for when comparing safety [31]. Even if the reliability of a sprinkler system is fairly high and the expected outcome from a system is acceptable, it does not imply the distribution of outcomes is acceptable. The consequences in case a system does not reach the expected function may be catastrophic and might not be accepted by society, which will imply great effects on the market and development of technology.

This section will evaluate how the implicit fire safety in a prescriptive design will be affected by a change to FRP composite in order to establish the needs for verification. It will be done by investigating characteristic properties of a system for fire safety, suggested by [31], and how these will be affected. The effects when changing from steel (Fe) to FRP composite are marked in table E4 and explained subsequently.

Table E4. Matrix used to get an overview of the effects from a change posed by an alternative design and arrangements. The upper and lower case "x" markings denote significant and minor changes and the plus and minus signs describe if the effect can be discerned positive or negative

Fire safety properties	Change				
	Will the property be affected?				Implications for safety?
	Fe → FRP	S1	S2	S3	Fe → FRP
Human intervention	x				0
Complexity in fire protection strategy	X				-
Fire protection complexity	x				0
Flexibility	x				0
Sensitivity	x				x
Reliability	X				-
Vulnerability	X				-

The markings in the matrix above have the same meanings as in table E3, except minus and plus signs have also been used to describe if an effect can be discerned positive or negative. The "S" followed by a number represents a possible supplementary measure, the effect of which can be evaluated through the matrix. Below follow further discussions on how each of the fire safety properties are be affected by a change from steel to FRP composite and what the effects imply regarding the needs for verification.

Human intervention

This property does not merely describe human intervention as an organisational measure, i.e. human actions as safeguards. It should rather be seen as an illustration of the human role in technical systems and how systems depend on humans in order to be functional. The impact of human intervention on the safety level is significant but hard to model because of the inherent uncertainties. As mentioned earlier, active systems generally contribute with more uncertainties than passive systems, but human intervention is even less reliable. Human errors are common and often the triggering actions setting off incidents. Therefore it is meaningful to establish if the novel systems for fire safety will be more depending on human intervention than a prescriptive design. A higher degree of influence from human intervention will invoke a more sophisticated verification [31].

A change from steel to FRP composite will imply new routines in order to assure the quality of FRP divisions. There need to be stringent standards for repair, maintenance and control to verify that penetrations are carried out correctly and divisions are refitted with sufficient insulation. This issue will be important in a design with FRP composite in order to prevent fire spread, but it is relevant also on steel ships. Other areas where human intervention plays a great role are in systems for fire safety, where human actions are critical for the consequences of a fire. Manually activated sprinkler systems or general alarms are common key issues as well as decisions for fire-fighting and search and rescue made by crew, based on their perception of the severity of the fire. These decisions will rather depend on the training, experience and personal qualities of the decision-maker than the structural materials. It appears many of the conditions, such as training, experience and routines for work and control, which are the basis for human intervention, could be slightly affected. However, even though this property will be affected by the change, it does not mean the safety of the design will be lower. Human intervention will affect the novel design similar to how it will affect the fire safety of a prescriptive design. New routines and training might even be a stimulating change to the crew. The limited experience of ships with FRP composite might although have a negative influence on human intervention. As a general conclusion, the changes in human intervention are not considered to have any significant effects on fire safety.

Complexity in the fire protection strategy

If it was possible it would be safe and uncomplicated if every single hazard was targeted with its own specific protection. There are, however, great benefits with coordinating risk control measures to target several parts of the fire protection strategy and more than one endpoint, as explained above. Building interdependent protection chains will, however, not only result in a complex network, which can be hard to comprehend, it will also provide conditions for common cause failures (CCFs). When several risk control measures are replaced by one measure, or by many dependant measures, it will cause some protection barriers to fail. An example can be a failure in detection of a fire which will cause late responses in escape, fire fighting and sprinkler activation (if activated manually or as a result of detection). The relationships between systems can also cover dependencies, which can bring about hazardous and incontrollable "snow ball" (exponential) effects when several systems fail at the same time. Increased complexities in the fire protection strategy can get huge consequences if the designer is not aware of the relationships between protection chains. A fire protection strategy with high complexity therefore implies higher demands on verification [31].

A relevant example of how common cause failures can be mitigated is by dividing a construction into fire zones. This is accomplished in SOLAS by prescribing structural main vertical and horizontal zones (see e.g. Regulations 2 and 9). The division into structural fire zones will limit the consequences in case e.g. the sprinkler system fails to work as intended or if the fire fighting crew needs to fall back. A reduction in complexity may e.g. be the result when heat can no longer be conducted far through the structure and bring about fires where there are weaknesses in integrity. This is particularly the case for the engine room. However, even if the engine room is well isolated from the rest of the ship there are no other fire zone divisors in the base design, which could be relevant to target. The combustible surfaces represent another target for risk control measures. Additional mitigating efforts on the necessary to make up for identified deficiencies will inevitably also add to the already complex fire protection strategy. The total effect on complexity in the fire protection system is estimated negative but needs to be further verified.

Fire protection complexity

The function of a technical system for fire protection many times depends on the performance of several components or subsystems. For example, in order to get smoke ventilation to function the smoke needs to be detected, detectors need to be functioning, control systems need to work as intended, the ventilation openings must open and the supply of air needs to function. The same thing applies to sprinkler systems where detectors, sprinkler heads, pipes, control systems, pumps and, not the least, drainage need to be functioning in order to assure the expected function. Building technical systems depending on the function of many components will increase the complexity and inevitably the probability of failure since more sources and combinations for error exist. It is also common for technical systems for fire protection to be integrated with everyday functions, e.g. ventilation and control of doors. The cooperation with other systems will further enlarge the network of systems. It will increase the complexities and also the needs for verification [31].

The least complex fire protection is that of passive structures. They are generally quite independent from other influences even if those occur, e.g. doors, windows and penetrations. The overall change to FRP composite is on this level and will not imply any great increases in complexity. However, they require additional passive or active measures which will somewhat increase the complexity of the whole fire protection system. Care should be taken to design those systems as simple as possible. Other than that, there are no apparent increases in complexity in the fire protection system that will affect safety. The above changes should be taken into account and the effects verified even if changes in complexity are not considered to have any great negative effects on safety if the systems are designed in a smart way.

Flexibility

The possibility for a system to accomplish the expected function in different ways is called flexibility. Systems for fire safety can often achieve objectives by targeting different parts of the fire protection strategy (see figure E1). If prevention of fire sources fails there will be measures to prevent and limit exposure of fire, and if that fails there are measures to prevent and limit the effects from fire. Combining different independent risk control measures targeting different parts of the fire protection strategy will give the system several possibilities to e.g. control fire. It will make the system flexible, which also characterizes a measure of redundancy. If a change in the fire protection strategy will make a system less flexible it can somewhat be compensated by increasing the reliability, i.e. the probability for a system to obtain the expected function. A lower flexibility will although also increase the needs for verification [31].

Making structures of a ship in FRP composite will imply differences in the approach for fire fighting crew. There is no need for boundary cooling and with new gear the new material allows for fire fighting without entering the fire enclosure, which could be an additional measure for fire protection. Furthermore, if the probability for collapse is greater in the base design it can hinder fire fighting crew from accomplishing their task, which will reduce flexibility. The overall effect on flexibility posed by the base design is although considered minor and will not have any significant effect on safety.

Sensitivity

The sensitivity of a system describes the importance of conditions and assumptions for a system to function as intended. In a system for fire safety there might be conditions and assumptions necessary to make the design for fire protection sufficient. Will achievement depend on the number of people in the compartment, weather conditions, occurrence of fire sources, the activities in the space, if a fire was set off by arson, if a penetration is not properly insulated, on the furnishings or on a certain risk control measure such as the sprinkler system? Factors such as the activity in the compartment, how things are carried out or necessary restrictions will often increase the sensitivity of a system. Restrictions to activities and human behaviour are often hard to control and seldom given enough resources. An increase in sensitivity needs to be taken into account when verifying system safety [31].

When evaluating fire safety in the base design there are some functions of great importance for the design to perform satisfactory. The sprinkler system is one of the most important systems on board and will determine the consequences of a fire. This will, however, be the same in both designs with steel and with FRP composite. In spaces where FRD-60 is used a fire will although most likely be better contained in the space of origin. It makes such a design more less dependent on circumstances, such as the performance of fire fighting and sprinkler system. Furthermore, a fire on external surfaces will also be sensitive to the function of its protection, which will imply a difference between the designs. The effects on sensitivity by a change to FRP composite need to be further analysed in order to establish how the safety will be affected.

Reliability

The reliability of a system can be defined as the probability of achieving the intended function of a system. The reliability of a system is generally connected with the probability of errors in the system but can also have to do with its ability to manage working strains. For example, the reliability of a sprinkler system will not only depend on the probability of technical failure but also on how likely it is that the specific fire is manageable. Low reliability naturally implies greater needs for verification and especially requires an evaluation of the consequences if the system fails [31].

The increased probability of a fire on exterior surfaces will inevitably imply a decreased reliability, regardless of the mitigating efforts. Drencher systems generally have high reliability and fire fighting crew can also assist to make the fire protection strategy more flexible and reliable. However, since the surfaces go from being non-combustible to combustible the reliability will be lessened as long as the surfaces are not made non-combustible again. This decrease in reliability can have minor effects on safety but the possible consequences of an uncontrolled external fire need to be analysed in order to verify the safety of the ship with FRP composite. The weakened thermal insulation for interior divisions will also decrease reliability when it comes to containing the fire in the compartment of origin. The reliability will definitely be affected by a change to FRP composite and as for the base design it the effects on safety are judged to be negative. These effects need to be further analysed in the risk assessment.

Vulnerability

Vulnerability is an undesired property which describes the ability of a system to survive internal and external strains. Internal vulnerability refers to the same characteristics as reliability whilst external vulnerability is determined by the probability that a system will function as designed when exposed to external stresses, such as arson, power outs, explosion, weather conditions etc. Some of the qualities characterizing low vulnerability are stability, perseverance and an ability to resist interference [31].

Common sources of vulnerability are activities and circumstances, which e.g. can lead to keeping doors open in some way and for some time. In case of fire it will provide additional oxygen to the fire and obliterate the limitation of smoke and fire spread. The general rule in prescriptive requirements is to provide two escape routes from all spaces in order to increase the reliability of successful escape. In the same way as doors are often kept open, they are also vulnerable to blockage, which will reduce the possibility to escape fire. These vulnerabilities can be reduced by a better understanding of the different functions in the system for fire protection, i.e. through education, training and experience. The above vulnerabilities are although the same in both the base design and prescriptive design. Except what is mentioned above concerning reliability there may be differences in vulnerability when it comes to maintenance and sabotage. Provided thermal insulation or active systems for fire protection may namely also become sources of vulnerability. Another point mentioned above is the external surfaces and how e.g. a drencher system will be a vulnerable component when it comes to extinguishing an external fire. Having only one assembly station is also a major source of vulnerability.

The fact that the novel design in this case implies a change from steel to FRP composite in the whole structure could both make the ship more and less vulnerable, depending on the implemented risk control measures. Some of the properties represented in the sections above are closely related to the vulnerability of a system, which makes it hard to delimit the changes in this property. From the discussions, the general conclusion is although drawn that the vulnerability of the fire protection will be affected and that the overall effects on safety could be negative. This, however, needs to be further investigated throughout the assessment.

Fire development

In the previous analyses, characteristics of the base design have been investigated in order to ascertain the impact of the novel FRP composite structure on fire safety. In this section the above revealed differences are discussed with regards to fire dynamics and based on diverse tests carried out at SP Technical Research Institute of Sweden [2, 16]. This suggests how differences between the structures may affect the fire development from a general point of view. The analysis aims to identify differences for inclusion in the proceeding analysis of fire safety. The first sections consider the internal spaces in different stages of a fire whilst exterior surfaces are discussed separately in the following.

Ignition and the first stages of an enclosure fire

Differences in routines for e.g. maintenance and repair will imply dissimilarities when it comes to fire sources. It is, however, justified to assume neither the probability of ignition nor the first development of enclosure fires will be considerably affected by the new design of load-bearing structures. Ignition sources will for the most part be alike even if they are hard to restrict on passenger ships, especially when including arson as a possible source of fire. The first stages of a fire do not depend on the load-bearing structures but are rather dependable on conditions such as ignition sources, the availability of flammable materials, surface materials of divisions, ventilation openings, fire control installations, etc. for the most part are identical in the two designs. In some spaces there will although be naked FRP composite without a protective surface or insulation. In this case the surfaces may contribute to the fire development at an early stage. Even if ignition is very unlikely there need to be risk control measures implemented to care for detection and extinguishment in those spaces. A fire should at this stage be detected and sprinkler system and other active measures will be set off and general alarms will be activated and evacuation initiated. It implies most fires will be controlled and extinguished in this early stage of fire development. That is before the combustible FRP composite, in the cases it is protected by a surface of low flame-spread characteristics, will take part in the fire. If a fire for some reason is given the possibility to develop, dissimilarities will eventually appear as the fire proceeds.

In spaces protected with FRD-60, the conditions are not likely to be worse than in a prescriptive design within the first 60 minutes. The outbreak and the first stage of a fire will be formed by settings within the space, such as possible ignition sources, fire load, ventilation openings, fire suppressing installations, etc. These circumstances will not be affected by the material in divisions and will be assumed identical to the conditions in a prescriptive design. Most likely a fire will be extinguished at an early stage but in case e.g. the sprinkler system fails it might progress into a fully developed fire. If the fire restricting installations fail, the differences with an alternative design can cause a somewhat higher temperature in the fire enclosure because of the increased thermal insulation in the composite construction. On the other hand, for the same reason, conduction of heat and propagation of fire to adjacent spaces would be delayed which improves fire safety. For spaces enclosed by FRD-60 the question is rather what will happen after 60 minutes of fire.

Structural divisions within the first 60 minutes

Spaces with unprotected surfaces contain very few ignition sources and limited furnishings and other combustibles (except the fuel tanks). The spaces are also generally closed and of rather small volume. This limits the oxygen available to stimulate fire development if a fire would appear, however unlikely. With a possibility to detect and extinguish fires in those spaces it may be possible to leave the surfaces naked.

Several spaces have surfaces of low flame-spread characteristics but no thermal insulation to protect the FRP composite divisions (which replace A class divisions with 60 minutes fire resistance). Tests have been carried out within the LASS project [2] with FRP composite bulkheads to find out how long they sustain fire exposure without thermal insulation. They showed that 10 minutes of fire resistance (of a fully developed fire) is expectable from a FRP composite panel of rather low quality. For the structure to be safe without protective passive measures there must be redundant active measures to control the fire within that time. Spaces with insufficiently protected surfaces, such as the accommodation space, therefore need more attention to gain sufficient safety [16].

In compartments protected by insulation (FRD-60) less heat will be conducted through the construction to adjacent compartments. It will diminish the risk for fire spread due to heat transfer through the enclosure boundary and delay propagation of fire to adjacent spaces. Down to the improved thermal insulation, the decks, bulkheads and ambience in adjacent spaces will be of ambient temperature, which could be advantageous in an escape situation and could increase the probability of a successful escape. More crew could help with the evacuation since there is no need for boundary cooling and the time available for escape and evacuation could be increased down to the improved thermal insulation. Evacuation should be designed to be completed within these first 60 minutes of improved conditions.

A non-extinguished fire will be confined within a space with FRD-60 boundaries for the first 60 minutes and it will be better contained than a prescriptive steel design. The structure will not be deformed even if a fire is uncontrolled and reaches flash-over, and heat will not be conducted to other places of the ship as in a steel design. A backside to the improved insulation could be an increased temperature in the fire compartment, which also would imply a somewhat increased heat release rate. However, the possible increase in temperature due to the decreased transmission of heat through boundaries will reasonably be minute. Furthermore, if a fire is not isolated in one space, e.g. if a door is left open, air from adjacent spaces will mix in which will make the effect even less significant. If a fire is isolated in one space it will lead to lack of oxygen and diminish the fire before any such effects would occur. The heat release rate is rather depending on the contents in the space which, however, would not affect theFRD-60 division as it is tested against 60 minutes of fully developed fire. An increase in temperature in the space of origin will probably be insignificant but there could still be reasons to confirm this. If the hypothesis is proved, the increased insulation will only lead to improved conditions for fire safety within the first 60 minutes.

The sensitivity to defects in fire protection should also be evaluated to ensure robustness of the novel design. Since the properties of an FRP composite structure are heavily based on the improved insulation capacity it needs to be established how sensitive the performance is to damage. Routines for maintenance and control need to be established in order to avoid exposure of combustible FRP composite. The consequences if the structure would be damaged, e.g. from maintenance, penetrations or sabotage still need to be investigated.

Structural divisions after propagation or deterioration

If active and passive risk control measures fail and the fire falls out of control, then the FRP composite will take part in the developing fire. This would in fact worsen the already hazardous conditions. Not only by adding more fuel to the fire and letting it continue but also by increasing the smoke production. This stage would only be reached after 60 minutes of uncontrolled fire if divisions are made up in FRD-60, which gives plenty of time to evacuate. In other spaces this stage could be reached significantly earlier if e.g. sprinkler system, manual extinguishment fail and the protective surface is deteriorated by fire. This scenario must be counteracted by additional risk control measures. Any magnitude of consequences will although not be acceptable if e.g. a sprinkler system fails. However, evacuations are not seldom protracted [28] and such a safety measure may therefore need to be combined with e.g. a safe place or redundancy.

Hence, open questions are still how much more likely a fire is to be uncontrolled in the base design and what the consequences will be? In the exceptional case of a time-consuming fire, collapse will be more likely to occur in the FRP composite construction, due to the properties of the FRP composite. Although, if only a part of the FRP composite is exposed to extraordinary heat or flames, the deterioration and collapse would be local. Furthermore, the load-bearing capacity of FRP composite is not very dependable on the loading but rather on the fire development and the time of exposure. The reference steel construction also suffers from deformation problems and strength deterioration when heated enough. In this case it is mainly dependable on the heat transfer properties of steel. Fire fighting will therefore be very difficult at this stage, both in the base design and a prescriptive design [16].

Exterior surfaces

In the exterior of the ship, a direct change from steel to FRP would not imply increased risks when it comes to ignition sources. Unprotected external surfaces would although definitely be a source of fire risk. Exchanging the external steel surfaces with combustible FRP composite will give an uncontrolled fire the ability to propagate vertically if a window breaks or if a door is left open. Except including external surfaces in the fire it could imply fire spread between decks and potential fire zones. This issue has been given much attention and full scale tests have been carried out on the matter in order to find suitable mitigating measures [16]. To produce FRP face sheets with low flame-spread characteristics and to install a drencher system for all external surfaces are the leading alternatives at the moment. If a drencher will be used to extinguish an external fire, the achievement will be sensitive to the function of the system which makes the drencher a vulnerable measure. New routines could also be an option, including fire fighting crew to preventing and limiting fire propagation on external surfaces. The change from “non-combustible” to “combustible but protected” implies a possibility for smoke production and fire spread in case the chosen risk control measure malfunctions and will therefore reduce reliability. The fact that external surfaces on ships are typically made of painted steel makes it hard to distinguish from prescriptive requirements what level of fire safety should be required. However, the unprotected external surfaces of the base design need to be managed and the effects evaluated in the assessment [16].
As a general conclusion, the ignition and the first stage of a fire development could be regarded equal on the novel design, comparing with the prescriptive design from a fire safety perspective. Depending on the proceeding scenario, differences between the designs might come in to play which will affect the fire safety negatively in the base design. The conditions in the spaces separated by FRD-60 divisions would better contain a fire but in all other spaces there are deficiencies that could stimulate the fire development, if not right away at least in case of an uncontrolled fire.

Data from fire hazard identification

Below follow the tabulated fire hazards for the concerned spaces divided in decks.

Deck 3

Compartment	Ignition sources	Initial fuels	Secondary fuels	Extension potential	Range of occupants	Target locations	Critical factors	Possible RCMs
Wheelhouse	Electrical failure in equipment or cables	Newspapers, magazines, books, tissues, etc.	Control panel and plastics in electrical equipment	WC	1-3	Medium sized space volume. All doors to the wheelhouse are generally closed (have automatic closing devices), none of which are possible to open for passengers. Windows are seldom open (not for ventilation).	Oxygen supply	A0-windows
	Fire spread surrounding areas	Clothes	Furniture and consoles	Accommodation space		Division surfaces, furniture and seats (all surfaces have LFS characteristics and upholstered chairs are certified Res. A.652(16))	Reaction to fire properties	Sprinkler redundancy
	Human error (smoking,	Textiles: Surface of seats	FRP composite underneath	Open deck space		Quality of FRP composite divisions, no thermal	Structural fire resistance	Trash cans in which a fire cannot survive

	lighter, match)		protective surface layer			insulation provided		
	Pyrotechnical equipment (emergency flares etc.)	Plastics in electrical equipment	Temporary baggage, backpack etc.	Exterior surfaces		Smoke detectors available	Detection	Provide clearly visible "no smoking" signs
		Trash/dust	Cables			Water mist system installed	Automatic extinguishment	Improved fire resistance by FRP composite material selection
			Upholstered furniture (certified)			Portable fire extinguishers available	Manual extinguishment	FRD XX (fire resisting division, where XX is 15, 30, 60, 90…) in combination with LFS or FRM surface lining
			Trash can					FRM (fire restricting material) on surfaces
			Papers, binders, books					

Compartment	Ignition sources	Initial fuels	Secondary fuels	Extension potential	Range of occupants	Target locations	Critical factors	Possible RCMs
WC	Smoking	Clothes	Trash bag	Accommodation space	0-1	Very limited space volume, door to the wheelhouse generally closed	Oxygen supply to fire	Self-closing doors

Electrical failure in equipment or cables	Toilet paper, tissues, newspapers, magazines, books, etc.	FRP composite underneath protective surface layer	Open deck		Surface materials (LFS)	Reaction to fire properties	Trash cans in which a fire cannot survive
Waste that ignites trash in waste basket	Waste bag	Toilet furnishing (sink etc.)	Wheelhouse		FRP composite without thermal insulation	Fire resistance	Improved fire resistance by FRP composite material selection
Fire spread from surrounding areas	Plastic material in the furnishings	Textiles			Smoke detector available	Detection	FRM (fire restricting material) on surfaces
Arson	Lighter fluid				Water mist extinguishment system (not required)	Automatic extinguishment	FRD XX (fire resisting division, where XX is 15, 30, 60, 90…) in combination with LFS or FRM surface lining
	Trash/dust				Portable extinguishers found in wheelhouse	Manual extinguishment	Internal divisions in B-0 around toilets (according to regulations)
					Quality of FRP composite divisions, no thermal insulation provided	Structural fire resistance	Provide clearly visible "no smoking" signs

Sprinkler redundancy

Door alarm, if not closed

Compartment	Ignition sources	Initial fuels	Secondary fuels	Extension potential	Range of occupants	Target locations	Critical factors	Possible RCMs
Open deck space	Human error (smoking etc.)	Plastics/rubber on deck	Composite structural materials	Wheelhouse	0-100	Impossible to limit, large open area with unlimited excess to oxygen	Oxygen supply	Surface with low flame spread characteristics (possibly non-combustible lining glued to surface)
	Arson	Deck equipment	Deck equipment	Ro-ro deck		Surface material, unprotected in base design provides fuel to potential fire without restrictions.	Reaction to fire properties	Surfaces of low flame-spread characteristics on all FRP composite surfaces
	Electrical failure	Garbage bags	Life rafts	WC		Quality of FRP composite divisions, no insulation provided in base design	Fire resistance	Extinguishing system/drencher
	Fire spread from other areas	Flammable liquid	Plastic seats and tables	Accommodation space		No extinguishing system provided	Automatic extinguishment	Clear no smoking signs and strict rules for crew
	Overheating or mechanical failure in	Diesel from Em.gen.	Luggage	Stairways to engine rooms		Portable extinguishers and fire hoses available	Manual extinguishment	EX classified equipment

	HVAC/Em.gen.							
	Electrical failure in HVAC/Em.gen.			Engine room ventilation			Risk of fire spread to exteriors for vulnerable overhang	Rounds by crew to make sure no one is smoking on deck
						No detection system	Detection	Smoke detectors
						Manual fire extinguishers	Extinguishment	

Deck 2

Compartment	Ignition sources	Initial fuels	Secondary fuels	Extension potential	Range of occupants	Target locations	Critical factors	Possible RCMs
Ro-ro deck	Human error (smoking etc.)	Hydrocarbon fuel	Dangerous goods	Surrounding exteriors	0-30 (30 in case of 5 people in 6 cars, normal case 10-15, possible with bus?)	Impossible to limit, large open area with unlimited excess to oxygen	Oxygen supply	Oil/fuel spill check by personnel
	Arson	Burning car	Vehicles	Open deck space on deck above		Trash cans, flammable oils	Amount of initial fuels	Forward boundary bulkhead towards accommodation space etc. covered by aluminium plating
	Car fire due to any failure	Deck equipment	Lighter fluid or other flammable	Accommodation space		FRP composite surfaces	Amount of secondary fuels	Redundant extinguishing system for ro-ro deck

		liquid or fuel.					
Electrical failure	Trash cans	Composite structural materials			Surface material, unprotected in base design provides fuel to potential fire without restrictions.	Reaction to fire properties	Surfaces of low flame-spread characteristics on all FRP composite surfaces
Bunkering	Plastics/rubber on deck	Deck equipment			Quality of FRP composite divisions, no insulation	Fire resistance	Maximum 25 passengers on board when oil tank is transported
Fire spread from other areas	Lighter fluids				Engines in vehicles, smoking	Ignition sources	Clear no smoking signs and staff controlling this
					Drencher under overhang according to requirements	Automatic extinguishment	Aluminium deck plating
					Portable extinguishers and fire hoses	Manual extinguishment	EX classified equipment
					Evacuation routes	Detection	Trash cans in which a fire cannot survive
					Surface material, unprotected in base design provides fuel to potential fire without restrictions.	Evacuation	Locked doors and control of no one on ro-ro deck during voyage

Compartment	Ignition sources	Initial fuels	Secondary fuels	Extension potential	Range of occupants	Target locations	Critical factors	Possible RCMs
							Risk of fire spread to exteriors and particularly under overhang	Adjusted deck with channel to collect potential oil spill (away from FRP composite).
Accommodation space	Electrical failure in equipment or cables	Textiles: Surface of seats and curtains	Textiles: Surface of seats and curtains	Void spaces	Maximum 200	Large space volume. All doors to the accommodation space are generally closed (have automatic closing devices) and only doors to toilets and to open deck (via stairs) are possible to open for passengers. Windows are not possible to open.	Oxygen supply	Division of the space into two fire zones (FRD60)
	Fire spread from surrounding areas	Clothes	Flammable liquids spilled by passengers, such as alcohol, lighter fluid etc.	Ro-ro deck		Combustible products, such as walls, furniture, luggage, ceiling and other secondary fuels (all surfaces have LFS characteristics and upholstered chairs are certified)	Heat release rate	Improved fire resistance by FRP composite material selection

Arson	Plastics in electrical equipment	FRP composite underneath protective surface layer	Open deck space above		Quality of FRP composite divisions, no thermal insulation provided	Structural fire resistance	FRM (fire restricting material) on surfaces
Human error (smoking, lighter, match)	Trash/dust	Luggage, baggage	Wheelhouse		Surfaces, furniture and luggage (all surfaces have LFS characteristics and upholstered chairs are certified Res. A.652(16))	Reaction to fire properties	FRD XX (fire resisting division, where XX is 15, 30, 60, 90…) in combination with LFS or FRM surface lining
	Newspapers, magazines, books, tissues, etc.	Upholstered furniture (certified)	Toilets		Information (smoking signs could probably be more visible, information given in speakers?)	Restriction of ignition sources	Information TV screens showing that smoking is not allowed, flammable liquids are not allowed to carry in the accommodation space (?) and the evacuation procedure
		Trash can	Fore deck		Information	Evacuation	Trash cans in which a fire cannot survive
			Cleaning cabinet		Water mist extinguishment system	Automatic extinguishment	Crew look through the accommodation areas after each trip
			Staircases		Smoke detectors	Detectors	Information is given before each voyage about evacuation routines through speakers
			Engine room		Portable fire	Manual	A0-windows

				ventilation		extinguishers available	extinguishment	
				Fuel tanks				Sprinkler redundancy
				Bow thruster spaces				Provide clearly visible "no smoking" signs
				Water tanks				Luggage area or area for "dangerous goods", such as lighter fluids
								Door alarms, if not closed

Compartment	**Ignition sources**	**Initial fuels**	**Secondary fuels**	**Extension potential**	**Range of occupants**	**Target locations**	**Critical factors**	**Possible RCMs**
WCs	Smoking	Clothes	Trash bag	Accommodation space	0-2 (normally 1 or possibly 2)	Door to the accommodation space, natural ventilation, limited space volume	Oxygen supply to fire	Self-closing doors
	Electrical failure in equipment or cables	Toilet paper, tissues, newspapers, magazines, books, etc.	FRP composite underneath protective surface layer	Open deck		Surface materials (LFS)	Reaction to fire properties	Trash cans in which a fire cannot survive
	Waste that ignites trash in waste basket	Waste bag	Toilet furnishing (sink etc.)	Void spaces		FRP composite without thermal insulation	Fire resistance	Improved fire resistance by FRP composite material selection

	Fire spread from surrounding areas	Plastic material in the furnishings	Luggage			Smoke detector available	Detection	FRM (fire restricting material) on surfaces
	Arson	Lighter fluid				Water mist extinguishment system (not required)	Automatic extinguishment	FRD XX (fire resisting division, where XX is 15, 30, 60, 90…) in combination with LFS or FRM surface lining
		Trash/dust				Portable extinguishers found in accommodation space	Manual extinguishment	Internal divisions in B-0 around toilets (according to regulations)
						Quality of FRP composite divisions, no thermal insulation provided	Structural fire resistance	Provide clearly visible "no smoking" signs
								A0-windows
								Door alarm, if not closed
								Sprinkler redundancy

Compartment	Ignition sources	Initial fuels	Secondary fuels	Extension potential	Range of occupants	Target locations	Critical factors	Possible RCMs
Ventilation casings	Electrical failure (almost no electrical equipment)	Dust, trash	Structural FRP composite material	Ro-ro deck	0	Very limited space volume. Door/hatch, normally closed except in case of inspection. Ventilation from the engine room (fire damper) and open vent	Oxygen supply to fire	Ex classified equipment in the space

					to ro-ro deck.		
Fire spread from surroundin g areas	Grease	Cabling	Stairway		Surface material, unprotected in base design provides fuel to potential fire without restrictions.	Reaction to fire properties	No cable penetrations or other unnecessary ignition sources
Hot surfaces	Cabling		Engine room		Quality of FRP composite divisions	Structural fire resistance	Surface materials of good reaction to fire properties (LFS)
			Void spaces		Smoke detectors not available	Detection	FRM (fire restricting material) on surfaces
			Accommodation space		Means for manual extinguishment are provided on ro-ro deck e.g. portable extinguishers.	Manual extinguishment	FRD XX (fire resisting division, where XX is 15, 30, 60, 90…) in combination with LFS or FRM surface lining
			Open deck space above		No automatic fire extinguishment system	Automatic extinguishment	Sprinkler system
						Possible fire growth rate and heat release	Fognail for manual fire extinguishment from outside
							Improved fire resistance by FRP composite material selection

Compartment	Ignition sources	Initial fuels	Secondary fuels	Extension potential	Range of occupants	Target locations	Critical factors	Possible RCMs
Fore deck	Human error (smoking etc.)	Plastics/rubber on deck	Composite structural materials	Surrounding exteriors	0-2 (only crew in case of mooring)	Impossible to limit, large open area with unlimited excess to oxygen	Oxygen supply	Surfaces of low flame-spread characteristics on all FRP composite surfaces
	Arson	Deck equipment	Deck equipment	Wheelhouse		FRP composite surfaces	Amount of fuels	Extinguishing system/drencher for fore deck
	Electrical failure	Garbage bags	Life rafts	Accommodation space		Quality of FRP composite divisions, no insulation provided in base design	Fire resistance	Boundary bulkhead towards accommodation space with thermal insulation on the inside (FRD60).
	Fire spread from other areas	Flammable liquid		Void spaces		Surface material, unprotected in base design provides fuel to potential fire without restrictions.	Reaction to fire properties	Clear no smoking signs and strict rules for crew
				Bow thruster spaces		No extinguishing system provided	Automatic extinguishment	EX classified equipment
						Portable extinguishers and fire hoses are not available	Manual extinguishment	
						No automatic fire extinguishment system	Automatic extinguishment	
						No detection system	Detection	

			Risk of fire spread to exteriors for vulnerable overhang

Deck 1.5

Compartment	Ignition sources	Initial fuels	Secondary fuels	Extension potential	Range of occupants	Target locations	Critical factors	Possible RCMs
Voids	Electrical failure, e.g. overheating, shortcut	Dust, trash	Structural FRP composite material	Ro-ro deck	0 (1 in case of inspection)	Door/hatch, normally closed except in case of inspection. Otherwise only an approx. 50 mm diam. ventilation penetration is provided.	Oxygen supply to fire	Ex classified equipment in the space
	Fire spread from surrounding areas	Grease, oils	Cabling	Steering gear		Surface material, unprotected in base design provides fuel to potential fire without restrictions.	Reaction to fire properties	No cable penetrations or other unnecessary ignition sources
		Cabling	Combustible piping and insulation	Engine room		Quality of FRP composite divisions	Structural fire resistance	Surface materials of good reaction to fire properties (LFS)
			Plastics in electronics	Adjacent void spaces on deck 1		Smoke detectors are not available	Detection	FRM (fire restricting material) on surfaces
				Accommodation space		No means for manual extinguishment are provided, e.g. portable extinguishers.	Manual extinguishment	FRD XX (fire resisting division, where XX is 15, 30, 60, 90…) in combination with LFS or FRM surface lining
						No automatic fire extinguishment system (e.g. sprinkler system)	Automatic extinguishment	Sprinkler system

							Possible fire growth rate and heat release	Fognail for manual fire extinguishment from outside
								Manual extinguishment system/routine
								Improved fire resistance by FRP composite material selection
								Hatch alarm, in case not closed
								Smoke detectors

Deck 1

Compartment	Ignition sources	Initial fuels	Secondary fuels	Extension potential	Range of occupants	Target locations	Critical factors	Possible RCMs
Steering gear space	Arson (only crew since hatch is locked, possible to open from below)	Grease/hydraulic oil	Grease/hydraulic oil	Engine room (insulation in engine room)	0 (1-2 persons in connection with service)	Door/hatch, if not closed a ventilation opening (diam. approx. 100 mm) is provided to cargo deck	Oxygen supply to fire	Hatch alarm, in case not closed
	Human error (unmanned during operation)	Oil mist	Structural FRP composite material	Void space on deck 1.5		Surface material, unprotected in base design provides fuel to potential fire without restrictions.	Reaction to fire properties of surface materials	Improved fire resistance by FRP composite material selection

Electrical equipment (very limited amount, mainly lights)	Paper/trash (very limited)	Signal cable (very limited amount)	Ro-ro deck		Smoke detectors	Structural fire resistance	LFS (low flame spread) surfaces
Static electricity	Rags (very limited)	Tubing			No automatic fire extinguishment system (e.g. sprinkler system)	Manual extinguishment	FRM (fire restricting material) on surfaces
Fire spread from surrounding areas					No means for manual extinguishment are provided, e.g. portable extinguishers, however hydrant is provided on car deck.	Automatic extinguishment	B-class panels internally on divisions
					Quality of FRP composite divisions	Detection	FRD XX (fire resisting division, where XX is 15, 30, 60, 90…) in combination with LFS or FRM surface lining
						Fire growth rate	Sprinkler system
							Camera for hatch and fire detection
							Fognail for manual fire extinguishment from outside
							EX-classified equipment in compartment

Compartment	Ignition sources	Initial fuels	Secondary fuels	Extension potential	Range of occupants	Target locations	Critical factors	Possible RCMs
Engine rooms	Hot surfaces (normally insulated)	Grease/hydraulic oil	Grease/hydraulic oil pool and spray	Steering gear (FRD60)	0-1 (periodically unmanned engine room, typically 1 person <1 h/day)	Door closers A60/FRD60 doors	Oxygen supply to fire	Sprinkler system redundancy
Comment: Design fire: hydrocarbon fire igniting unprotected deck side	Electrical equipment causing statistic electricity or overheating (generator, lighting, main switchboard, enclosed battery system, heat fan, engine room fan, bearings, etc.)	Fuel (diesel)	Fuel (diesel pool and spray)	Void space on deck 1.5 (FRD60)		Ventilation system routine in case of fire, fire dampers	Reaction to fire properties of surface materials	Extinguishment system with inert gas
	Fire spread from surrounding areas	Cabling	Cabling, hoses	Cargo deck (FRD60)		Non-insulated surfaces below insulation (only LFS). FRD60 down to 300 mm below summer waterline.	Manual extinguishment	Fognail for manual fire extinguishment from outside

	Arson (two locked doors separating from passengers)	Plastic covers/electronics	Plastic covers/electronics, switchboard, fuse box etc.	Water tanks (FRD60)		Quality of insulation, FRD60	Automatic extinguishment	Stricter requirements for insulation of hot surfaces.
		Fuel/oil spray	Clothes	Staircase (FRD60)		Smoke and heat detectors	Detection	Alarm for doors in case they are not closed
		Paper/trash (very limited)				Water mist extinguishment system	Fire growth rate	FRD XX (fire resisting division, where XX is >60)
		Rags (very limited)				Portable fire extinguishers	Evacuation	FRM surface lining
						Hydrants on cargo deck		Camera for hatch and fire detection
						Insulation of hot surfaces.		EX-classified equipment in compartment
						Gas extinguishing system		Improved fire resistance by FRP composite material selection
Compartment	**Ignition sources**	**Initial fuels**	**Secondary fuels**	**Extension potential**	**Range of occupants**	**Target locations**	**Critical factors**	**Possible RCMs**
Water tanks	N/A							

Compartment	Ignition sources	Initial fuels	Secondary fuels	Extension potential	Range of occupants	Target locations	Critical factors	Possible RCMs
Fuel tanks	Static electricity in connection to filling of fuel.	Fuel (gases) in fuel tank	Fuel tank FRP composite material	Surrounding void spaces	0	Quality of FRP composite divisions	Fire integrity of tank/divisions	Not have any passengers on board during bunkering
Comment: Anders Lönnermark refers to SP project (2004:14) "Tank fire review" where ignition of diesel occurred when transferring diesel from one tank to another.	Fire spread from surrounding areas			Cargo deck		Integrity (insufficient supply of oxygen)	Oxygen supply to fire	Manual extinguishment ready during filling of tank
							Heating of tank/fuel, which could lead to leakage	Grounding of tanks

Compartment	Ignition sources	Initial fuels	Secondary fuels	Extension potential	Range of occupants	Target locations	Critical factors	Possible RCMs
Void spaces	Electrical failure, e.g. overheating, shortcut	Cabling	Structural FRP composite material	Fuel tank	0 (1 in case of inspection)	Door/hatch, normally closed except in case of inspection. Otherwise only an approx. 50 mm diam. ventilation penetration is provided.	Oxygen supply to fire	Hatch alarm, in case not closed

Fire spread from surrounding areas	Combustible piping and insulation	Cabling	Adjacent void spaces		Surface material, unprotected in base design provides fuel to potential fire without restrictions.	Reaction to fire properties	LFS (low flame spread) surfaces
		Combustible piping and insulation	Stairway		Quality of FRP composite divisions	Structural fire resistance	Improved fire resistance by FRP composite material selection
		Plastics in electronics	Water tanks		Smoke detectors are not available	Detection	FRM (fire restricting material) on surfaces
			Bow thruster space		No means for manual extinguishment are provided, e.g. portable extinguishers.	Manual extinguishment	Fognail for manual fire extinguishment from outside
			Accommodation space		No automatic fire extinguishment system (e.g. sprinkler system)	Automatic extinguishment	FRD XX (fire resisting division, where XX is 15, 30, 60, 90…) in combination with LFS or FRM surface lining
						Possible fire growth rate and heat release	Manual extinguishment system
							Smoke detectors
							Ex classified equipment in the space
							Sprinkler system

Compartment	Ignition sources	Initial fuels	Secondary fuels	Extension potential	Range of occupants	Target locations	Critical factors	Possible RCMs
Bow thruster spaces	Human failure in reparation work	Paper/trash (very limited)	Grease/hydraulic oil	Adjacent void spaces	0 (1-2 persons in connection with service)	Door/hatch, normally closed except in case of inspection. Otherwise only an approx. 50 mm diam. ventilation penetration is provided.	Oxygen supply to fire	Hatch alarm, in case not closed
	Hot surfaces (normally insulated)	Grease/hydraulic oil	Structural FRP composite material	Accommodation space		Surface material, unprotected in base design provides fuel to potential fire without restrictions.	Reaction to fire properties	Improved fire resistance by FRP composite material selection
	Electrical failure or overheating (generator, lightning)	Cabling	Cables (limited amount)			Quality of FRP composite divisions	Structural fire resistance	LFS (low flame spread) surfaces
	Fire spread from surrounding areas	Plastic covers/electronics	Tubing (limited amount)			No means for manual extinguishment are provided, e.g. portable extinguishers.	Manual extinguishment	In case of reparation, manual extinguishment equipment is brought down to the space (portable extinguisher or hydrant from above)
	Mechanical failure or overheating	Rags (very limited)				Smoke detectors	Detection	FRM (fire restricting material) on surfaces

	Arson (not easily accessible)					No automatic fire extinguishment system (e.g. sprinkler system)	Automatic extinguishment	FRD XX (fire resisting division, where XX is 15, 30, 60, 90…) in combination with LFS or FRM surface lining
							Possible fire growth rate and heat release	Sprinkler system
								Manual extinguishment system
								Fognail for manual fire extinguishment from outside

Compartment	Ignition sources	Initial fuels	Secondary fuels	Extension potential	Range of occupants	Target locations	Critical factors	Possible RCMs
Stairways	Electrical failure in equipment or cables	Cables	Ceiling and bulkheads (LFS)	Engine room	0 (sporadically 1 or possibly 2)	Doors to engine room and accommodation space are normally closed. Then only sparse natural ventilation from accommodation space.	Oxygen supply to fire	Door closer and locks to engine room and accommodation space.
	Fire spread from surrounding areas	Dust/trash	Furnishing (not allowed)	Accommodation space		The walls, floors and other surfaces in the staircase fulfil low flame-spread characteristics	Reaction to fire properties	Improved fire resistance by FRP composite material selection
	Arson	Wall decorations	Garbage bags (not allowed)	Void space		Quality of FRP composite divisions	Structural fire resistance	Fire damper also between stairway and accommodation space

Human error (smoking?)	Garbage bags	Ro-ro deck		No portable extinguishers available	Manual extinguishment	FRM (fire restricting material) on surfaces
		Engine room ventilation		Smoke detectors	Detection	FRD XX (fire resisting division, where XX is 15, 30, 60, 90…) in combination with LFS or FRM surface lining
				Water mist extinguishing system	Automatic extinguishment	Portable extinguisher
						Sprinkler redundancy
						Fognail for manual fire extinguishment from outside
						Door alarm, if not closed

Procon list

Since all effects on the safety level of a prescriptive design cannot be determined from deviated prescriptive requirements a number of additional evaluations were carried out. All pros and cons from a fire safety perspective were listed in this Procon list, where they were also rated by fire experts according to the Delphi method to provide guidance for the selection of fire hazards.

Pros and cons with the base design from a fire safety perspective	**Rating**
The ignitability of combustible external surfaces is not limited which implies more probable ignition.	-1
The use of combustible materials is not restricted on external surfaces, which implies fire spread is more likely (exchanging the external steel surfaces with combustible FRP composite will give an uncontrolled fire the ability to propagate vertically which, except including external surfaces in the fire, could imply fire spread between decks)	-4
Smoke production will be increased in case external surfaces take part in a fire (even if smoke production is not critical on open deck).	-1
Unprotected external surfaces need to be targeted somehow. However, the fire safety will then be sensitive to the function of the provided RCM/RCMs and the reliability of the fire safety will then be reduced regardless of the added measures	
The engine room bottoms are only protected with a surface of low flame spread characteristics more than 300 mm below the water line where a non-combustible surface is customary.	-2
Voids, auxiliary machinery spaces and tanks do not have non-combustible surfaces, as customary in prescriptive designs. It will affect fire growth and smoke production in case of fire. Oxygen supply is although likely limited.	-1
FRP composite divisions simply faced with surfaces of low flame spread characteristics may provide fuel to a fire since the underlying divisions are combustible. It will affect fire growth and smoke production in case of an extended fire.	-2
Since the thermal insulation provided in the engine rooms only works "one way" the engine rooms are not sufficiently protected from a fire occurring in adjacent spaces. In sufficiently insulated FRP composite surfaces towards the engine room are found on ro-ro deck and in stairways where A-60 and A-30 standards apply, respectively.	-1
No evacuation station redundancy is provided	-3
Structural integrity according to A-class standard is not fulfilled by divisions in the base design since FRP composite is combustible. A continuing fire could bring about a local collapse when the FRP delaminates from the core which imposes a risk to fire-fighting crew (even if it has been proven to be a slow process). Fire fighting will however be very difficult at this stage, both in a design with FRP composite and a prescriptive design. This applies to principally all divisions on the ship (except e.g. toilets).	-3
The toilets are enclosed by combustible FRP composite with surfaces of low flame spread characteristics instead of by B-0 divisions (30 minutes of structural fire protection).	-1
The ro-ro deck is not thermally protected against fire in the accommodation space, in the steering gear and on the overhang for 60 minutes as required but simply by FRP composite.	-2

The accommodation space is not thermally and structurally protected against fire on ro-ro deck, as required (A-60), but simply by FRP composite.	-4
The steering gear is not thermally and structurally protected against fire on ro-ro deck, as required (A-60), but simply by FRP composite.	-3
The overhang is not thermally and structurally protected against fire on ro-ro deck, as required (A-60), but simply by FRP composite and drencher.	-1
The cleaning cabinet is not sufficiently protected against fire spread from the accommodation space (A-60 required), but simply by FRP composite with surfaces of low flame spread characteristics.	-1
The accommodation space is not sufficiently protected against fire spread from the cleaning cabinet (A-60 required), but simply by FRP composite with surfaces of low flame spread characteristics.	-2
The life rafts on fore deck are not separated by A-60 divisions but simply by FRP composite.	-2
A fire will be more likely to be contained/isolated in the engine room on account to the improved thermal insulation in comparison to an A-60 construction. Hence, steering gear spaces, water tanks, voids and the stairways are thermally protected from an engine room fire for 60 minutes even though A-0, A-0, A-0 and A-30 is required.	2
The above (improved containment) is also true in case the sprinkler system fails and openings are closed which will induce reduced sensitivity to these failures (safety is thereby not as dependant on sprinkler system and fire fighting)	1
A long-lasting fire could bring about a major collapse which could affect great parts of the ship	-2
The fuel tank spaces are left without any passive fire protection in the base design even though A-60 is required towards the accommodation space above and A-0 toward the surrounding void spaces	-1
Relieving boundary cooling will reduce complexity in the fire protection strategy	1
The fire fighting routines and maintenance will need to be changed, which implies new routines and inexperience	0
In steel structures heat can be conducted far through the structure and bring about fires where there are weaknesses in integrity. In an FRP composite construction heat will not be easily conducted to other places which will reduce the complexity in the fire protection strategy.	1
Down to the improved thermal insulation where FRD60 is used, the adjacent decks, bulkheads and ambience in adjacent spaces will be of ambient temperature, which could be advantageous in an escape situation and could increase the probability of a successful escape.	2

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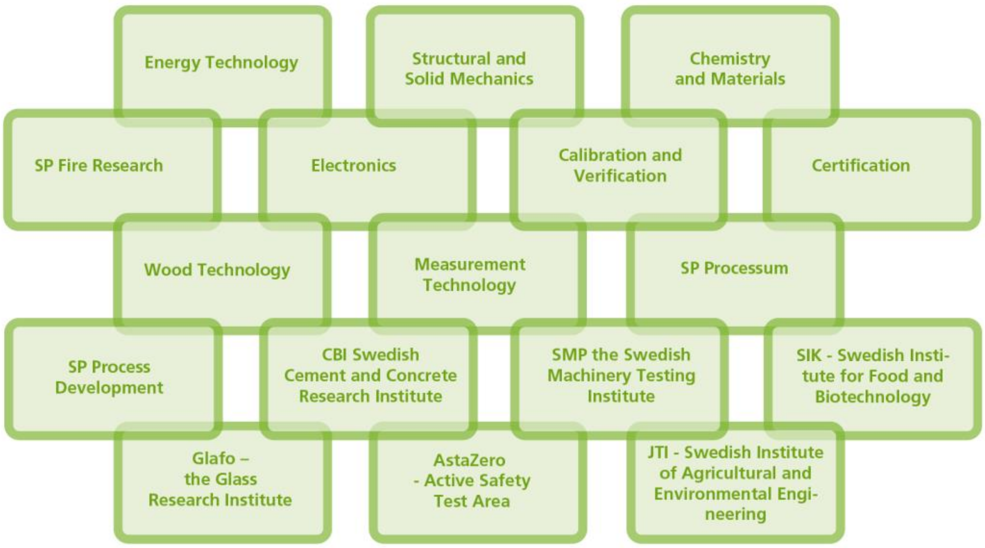

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