FIRST – Fire strategies for unmanned island ferries

Appendix 3 – Holistic fire safety strategy for small autonomous ferries

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Content

1 Methodology

1.1 Risk approach – performance-based design

This appendix reports the development and suggestion of a fire safety strategy for autonomous vessels.

A fire safety strategy would typically be divided into two parts, a pre-ignition part and a post-ignition part. The former aims at preventing fire events, whereas the latter aims at mitigating fire events. The scope of the present work is limited to the situation where a fire actually occurs. By looking at post-ignition situations, it is possible to explore the necessary design choices to make in order to ensure the safety of passengers and crew. In the present document, the notion of "fire safety strategy" refers to the design choices made and procedures developed to mitigate fire events (Figure 1-1)

The work reported in Appendix 1 highlighted the limitations in the existing guidelines for autonomous vessels, and the lack of guidelines or regulations from the Danish authorities specifically. The project team therefore chose to treat the topic with a performance-based approach stemming from a risk analysis.
The given constraints to work with all emerge out of the implementation of new technologies – autonomy and electric propulsion. This leads to a situation where there is limited to no guidelines, data, or user experience (again within the narrow scope of fire safety). As a result, the project team hypothesises that a probabilistic risk analysis would make little sense, as it would not be possible to ground any probability in real-life experience. Specific points of uncertainty include the behaviour of passengers when facing a fire they can see, the likelihood of a battery pack to fail so that a fire starts, or the probability of an electric bike to ignite.
As a result, the risk analysis is limited to the identification of hazards following a Hazard and Operability (HAZOP) procedure [1,2] out of which fire scenarios are treated in a deterministic way. Mitigation solutions are developed in a performance-based thinking, on the basis that all the scenarios are equally likely to occur. The following equation summarises the approach chosen herein:

Fire safety strategy = HAZOP + performance-based design

The performance based approach advocates for a closer position to "holistic" design by seeing the ship as an integrated system, and by including human factors in the design.
Seeing the ship as a system means that solutions for a given room should find their place within the overall design, without conflicting with choices made elsewhere. This also means that the design attempts to maximise the unicity of technical solutions, and designs the interfaces between rooms and interactions between rooms and systems so as to maximise the level of safety. The specific structure of the performance-based design following a what-if structured room-by-room approach is details in Section 1.2.
Human factors focus on both the Master of the ship and the passengers. The study reported in Appendix 2 provides input for the fire safety design, as mentioned in the present report at relevant places. It brings information on passenger reactions and behaviours, as well as expectations in the context of autonomous vessels and of safety in general. For further insight, the reader is referred to Appendix 2 and Section 3 of the present report.

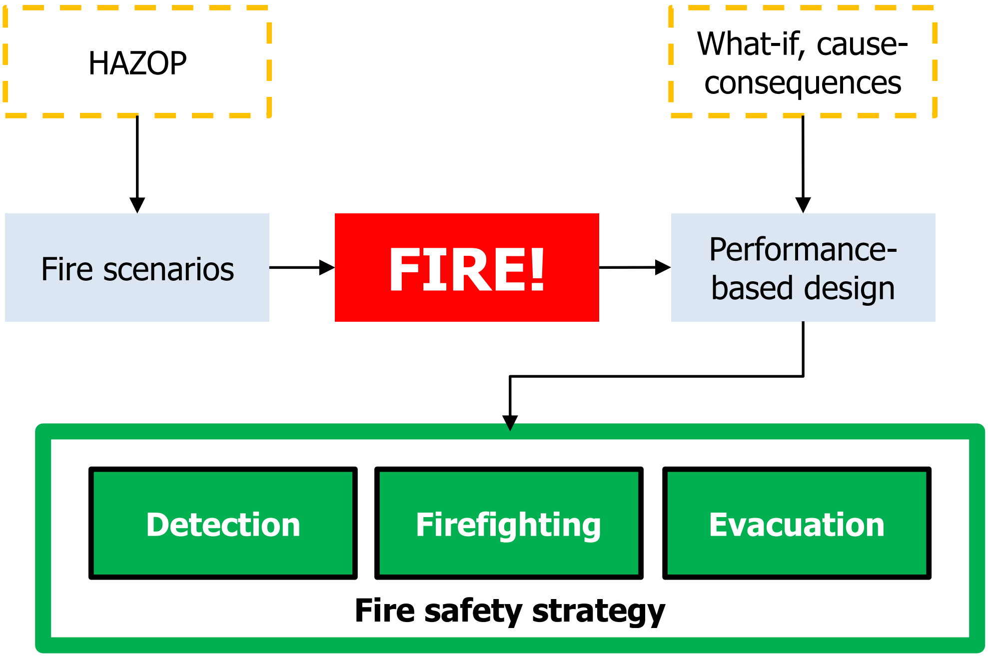

Figure 1-1 – Schematics of the fire safety strategy as approached in the present project

1.2 Performance-based design - What-if scheme

The choice to approach the fire safety strategy in a performance-based manner comes necessarily from the lack of regulations and prescriptive guidelines in this topic. Functionally, however, it allows a large degree of freedom with respect to engineering decisions in order to achieve the fire safety objectives. This method serves the double purpose of proposing a possible fire safety strategy for a small autonomous ferry, and to illustrate the design possibilities and benefits obtained out of solely focussing on the safety objectives rather than pre-made stiff guidelines.
As a first observation, and as the following sections will illustrate, this approach requires increased engineering attention, leading to a more extensive design process. However, as a qualitative observation, savings in materials, increased safety, and optimised solutions may balance out this initial investment.

The fire safety engineering team chose to follow a room-by-room approach to produce, paradoxically, a holistic fire safety strategy. The intention is that a room-by-room approach will identify necessary fire protection for each individual room, and at the same time highlight common themes between rooms to unify the solutions at the scale of the ship. Moreover, incompatibilities between individual room solutions can then surface and be treated accordingly.

Practically, to perform the room-by-room analysis, the team describes the chain of event of a fire in broad areas of focus. Each area of focus is addressed for a given room, accounting for the specificities of that room, and in a way that the fire safety objectives are fulfilled. The chain of events for a fire is given in Table 1.

Some of the necessary points to explore in order to protect a given room will answer questions valid for all rooms (e.g. how an alarm message is reported to the bridge, or which procedure should be followed for detection confirmation). The analysis thus produced serves as a basis for the next room. This method provides the advantage of revising the strategy with every new room as in an iterative process; it also highlights redundant themes which are then taken to the scale of the ship and answers are suggested so that functionality of the considered solutions is ensured in all cases.

Table 1 – Chain of events for the development of a fire situation on board the small autonomous ferry

ID#	Event
1	Fire occurs – what scenario is considered
2	Fire is detected
3	Master is presented with the alarm
4	Confirmation of detection
5	Passengers are informed of a "problem" and instructed to proceed to the muster station
6	Distress message is sent to shore
7	Return to port initiated
8	Firefighting initiated
9	Continuous communication with passengers and shore support
10	Dock ship at ferry terminal
11	Evacuate passengers

To unfold the chain of events of a fire within a given room, the fire safety engineering team followed a semi-structured What-if scheme. Key words guide the questions asked within the scheme. A limited selection of words with an intentionally vague scope are used to ensure the main themes are covered without limiting the flow of ideas. These words are:

- Master's perspective
- Master's behaviour
- Technical failure
- Redundancy
- Fire spread
- Active systems
- Passive protection
- Passengers

Advantages of the proposed approach:

- Addresses the specific fire scenarios highlighted in each individual room
- Allows defining necessary protection for each individual room
- Highlights common themes between rooms so as to provide a unique answer to them at the scale of the ship
- Investigates the interaction between adjacent rooms
- Functions as an iterative process, in the sense that looking through the next room works as a revision of the choices and possibilities identified for the previous room

1.3 Safety objectives

A performance-based approach can only be coherent if seen as the effort of a design team to fulfil a given set of objectives. In the present case, the objectives concern fire safety specifically. The fire safety objectives given herein are close to those stipulated in SOLAS [3]. The scope of the work, as mentioned in Section 1.1, is limited to the situation where a fire actually occurs. This rules the first fire safety objective of SOLAS out of the scope of the present work ("*prevent the occurrence of fire and explosion*"). The other objectives are still valid. The fire safety objectives in this project are:

1- **Reduce the risk to life caused by fire**
2- **Reduce the risk of damage caused by fire to the ship, its cargo and the environment**
3- **Contain, control and suppress fire and explosion in the compartment of origin**
4- **Provide adequate and readily accessible means of escape for passengers and crew**

The project team formulated an additional requirement specific to this study as a foundation for theoretical exploration:

5- Make the ship its own best lifeboat

This last fire safety requirement aims at exploring the possibilities to design fire safety on board the ship in such a way that an evacuation would not be a necessity, thus avoiding the risks associated with this procedure.

Practically, the fire safety objectives stated above serve as design guidelines to express functional requirements for given technical solutions. These functional requirements are part of the findings of this project.

2 Fire safety design process

This section presents the results of the risk analysis performed according to the methodology described in the previous section.

2.1 Identification of hazards

The identification of hazards took the form of HAZOP workshops [1,2]. The fire safety engineering team led the workshops to identify potential fire scenarios. The fire scenarios consist of an ignition source with a specific cause, in a specific room. Additionally, the team identified the available fuel sources that could contribute to a fire in a specific room. Table 2 presents the available fuels.

Table 3 presents the identified scenarios.

Table 2 – Available fuels in each room of the ship

Location	Available fuels
Battery room	Plastic enclosures
	Internal polymer separator of batteries
	Cable insulation
	Electrolytic fluid
Switchboard room	Electrical connector material
	Cable insulation
	Rubber gaskets
	Vibration damping rubber
	Electrical components
	PCBs
	UPS units
Propulsion room	Wire insulation
	Lubricant
Open deck	Paint
	Passenger belongings
	Litter
Passenger accommodation	Furniture and upholstery
	Wall linings
	Passenger belongings
	Paper
Ro-Ro deck	Batteries
	Gasoline
	Plastics
	Paints and coatings
	Rope and mooring equipment
	Rubber (gaskets and fenders)
Sun deck	Litter
	Plastic furniture
Bridge	Electrical components
	Cables
	UPS unit
	Furniture and upholstery
	Wall linings
	Litter
	PCBs

Table 3 - Fire risks identified during the HAZOP workshops

ID#	Location	Ignition source	Cause
1	Battery room	Battery thermal runaway	Overcharging
2			Punctured cell
3			Elevated ambient temperature
4		Battery short circuit	Loose connections
6			Forgotten tools (maintenance)
7			Corrosion
8			Damage to components
9			Water ingress
10			Cooling water leakage
11		Battery overheating	Faulty temperature sensors (BMS)
12			Cooling pump failure
13			Clogged filters at sea chests
14			Fouling at heat exchangers/sea chests/box cooler
15		Hot surfaces	Cooling pump failure
16		Fluorescent lights	Loose connections
17			Faulty fixtures
18			Vibrations
19	Switchboard room	Short circuit in cabinet	Corrosion
20			Loose connection at terminal blocks, relay…
21			Forgotten tools
22			Damage to components
23			External contamination (metal shavings, dust…)
24			Improper design
25			Water ingress
26		Overheating	High environmental temperatures
27			AC unit failure
28		Electrical arcing	Loose connections at terminal blocks, relay…
29			Improper design
30			Unauthorized or improper maintenance
31		Fluorescent lights	Loose connections
32			Faulty fixtures
33			Vibrations
34	Propulsion room	Electric motor	Static electricity, sparks/arcing from rotor or stator
35		Electric motor overheating	Failed ventilation
36		Bearing failure	Friction sparks from bearings
37	Open deck	Personal electronic devices	Battery malfunction or short circuit
38		Fluorescent lights	Loose connections
39			Faulty fixtures
40			Vibrations
41		Arson	
42	Passenger accommodation	Heating elements (electric radiators, hand driers…)	Malfunction
43			Used for drying textiles
44		Personal electronic devices	Battery malfunction or short circuit
45		Fluorescent lights	Loose connections
46			Faulty fixtures
47			Vibrations
48		Fireworks	Spontaneous combustion, ignited by friction
49			Used indoors by passenger
50		Arson	
51	Ro-Ro deck	Electric bikes	Battery malfunction or short circuit
52		Scooters (combustion engine)	Fuel leak
53			Battery malfunction
54		Personal electronic devices	Battery malfunction or short circuit
55		Cigarette	Dropped in bins

56		Fluorescent lights	Loose connections
57			Faulty fixtures
58			Vibrations
59		Fireworks	Spontaneous combustion, ignited by friction
60			Unlucky use by passenger
61		Arson	
62	Sun deck	Cigarette	Dropped in bins
63		Personal electronic devices	Battery malfunction
64		Fireworks	Spontaneous combustion, ignited by friction
65			Unlucky use by passenger
66		Arson	
67	Bridge	Short circuit	Loose connection
68			Corrosion
69			Damaged component
70			Water ingress
71			Cooling water leakage
72		Overheating	High environmental temperature
73			AC unit failure
74			Cooling system failure
75		Electrical arcing	Loose connections at terminal blocks, relay…
76			Improper design
77			Unauthorized or improper maintenance

2.2 Room-by-room

2.2.1 Qualitative analysis

The qualitative analysis was carried out following the method outlined in Section 1.2. This approach performs well in the sense that rooms are systematically screened according to the development of a fire, to deliver an adapted solution in every case. This is a way to ensure that the fire safety strategy mitigates all foreseen cases.
The method is extensive, and each room can yield an analysis of several pages. This section proposes an example, applied to the propulsion room. More rooms are covered in Appendix B of the present document.

The analysis follows the development of events as proposed in Table 1. Some of these points do not command an outlook specific to the given room, but are relevant for all the rooms. They are then developed in Section 2.3.

#1 – Fire occurs – what scenario is considered
Fire occurs in the propulsion room due to overheating of the electric engine.

#2 – Fire is detected
The detection system is assumed to be a traditional detection system. If it does not detect the fire, a backup system is needed. The backup system is of a different kind than the first one, and is independent from the first one. Its input is displayed on the same visualisation system in the bridge.
<u>Main detection systems:</u>

- Smoke sensor (most likely standard point detector)
- Temperature sensor – close to the electrical motor, on it, or high up in the room? (could be thermocouple, or gas-filled tube)

Additional detection system:

- CCTV with image analysis software (e.g. smoke pattern), with permanent lighting of the room with LED light

Reasons for standard point smoke detector to fail:

- Ventilation extracts smoke out of the detector's way (mitigation: ventilation design/detector placement)
- Clogged by dust, banana flies (mitigation: air is filtered, clean operation (electric), regular maintenance scheme, 5-year check up)
- Vibrations (mitigation: very limited due to quiet operation (electric))
- In general, smoke detector is not mentioned as having failed in marine fires

Reasons for a thermocouple to fail:

- Wiring (mitigation: gives a crazy reading so failure is detected by the system)
- Corrosion (mitigation: quick literature review seems to indicate that thermocouples are corrosion-resistant)

Reasons for CCTV to fail:

- Loss of light (mitigation: automatic feedback, detected by the system)

#3 – The Master is presented with the alarm

This point is relevant for all rooms and is detailed in Section 2.3.

#4 – Confirmation of detection

Traditionally this is done by the crew once an alarm has been triggered. In this case, the suggestion is that the ship does it alone without referring to the Master. This will increase response speed, as required by the strategy to take swift action.

Three detection means are installed in the room. This covers the issue of redundancy. As the systems react to different properties of fire (smoke, light, and heat), they measure different metrics. Two measurements coming from two different systems are then assumed to provide confirmation of detection. This way the ship can detect the fire and confirm detection within a short time and without involving the Master.

The risk is that fire detection from two different metrics can take time, and the delay between initial detection and confirmation could be large. The mitigation is to install systems with a maximum response time deemed acceptable, and this benchmark could be the standard sensitivity of a point smoke detector. The other systems shall not detect a fire within a longer time frame than that.

#5 – Passengers are informed of a "problem" and instructed to proceed to the muster station

This point is relevant for all rooms and is detailed in Section 2.3. The situation where the fire is visible by the passengers will be addressed separately and make the object of its own procedure.

#6 – Distress message to shore is sent

This point is relevant for all rooms and is detailed in Section 2.3.

#7 – Return to port initiated

This point is relevant for all rooms and is detailed in Section 2.3.

In the particular case of the propulsion room, it may be that return to port could be initiated but not completed, according to the damage done by the fire (or the damage which initiated the fire). In the case where the ship lost the capacity to sail, the question revolves around evacuation, detailed in **#11**.

#8 – Firefighting initiated

A damper is installed on the ventilation outlet of the propulsion room to avoid fire spread via the ventilation system.

In the specific case of the propulsion room, active firefighting solution could be a CO_2/inert gas system due to the presence of electric components. This solution would also support operation of the system for a longer time (or ensure it would keep operating up to docking, according to the criticality of the ignition situation). This system requires the activation of the ventilation dampers prior to its release. It should also be entirely certain that no person is present in the room, as a human would not likely survive the discharge of the system.

It recommended to avoid using powder-based solutions.

Upon confirmation of detection (**#4**) the ship triggers the closing of the ventilation dampers and discharge of the CO_2/inert gas system. Pressure sensors on the gas canisters monitor the proper release of the gas. Temperature sensors in the room and CCTV (**#2**) monitor the effect of the gas release on the development of the fire. These pieces of information are reported to the bridge.

Technical reasons why the CO_2/inert gas system would not trigger:

- Valve failure (mitigation: choose quality components, include manual release possibility, regular maintenance)
- Clogged pipes, dirt build-up over time (mitigation: non-return valve preventing external contaminants from entering the piping, secondary system would keep positive pressure in the pipes, regular maintenance/risk management scheme)
- Ruptured pipe, due to explosion or collision (mitigation: if a fire is triggered by one of these events, we have immediate evacuation)
- Signal issue between central system and gas release (mitigation: redundant fixed wiring with checkup at installation and commissioning, possibility for manual release, regular maintenance/risk management scheme, system self-check)
- Out of gas (mitigation: message is displayed on the monitoring screens in the bridge, and info communicated to the shore-based center)

Human reasons why the CO_2/inert gas system would not trigger:

- Failure to check that system works
- Negligence
- Non-adapted procedures

If the CO2/inert gas system is not efficient:

- Possible to trigger twice (as recommended by some accident reports)
- Passive protection is dimensioned to withstand the entire duration of the fire (see example in Section 2.2.2)

#9 – Continuous communication with passengers and shore support

This point is relevant for all rooms and is detailed in Section 2.3.

#10 – Dock the ship at ferry terminal

This point is relevant for all rooms and is detailed in Section 2.3.

This specific scenario concerns the propulsion room, so there may not be the possibility to sail back to port in this case. **#11** on evacuation may be a more relevant area to consider.

#11 – Evacuate passengers

This point is relevant for all rooms and is detailed in Section 2.3.

2.2.2 Quantitative analysis

This part proposes an example of fire safety engineering performed on one of the battery rooms. It assesses the performance of the passive fire protection installed between the battery room and the passenger accommodation located above it. The idea is to document whether the passive protection can ensure that the temperature in the passenger lounge does not rise above a level requiring evacuation of the passenger. This way, it would be possible to keep the passengers in the passenger accommodation for the entire duration of the fire, and evacuation would not be a necessity. Both the options of returning to port and waiting for rescue would be possible, in a safe manner.

The intention is to illustrate an equivalent level of performance to a prescriptive design. Showing this point without the need to use the lifeboats is a way to demonstrate redundancy, as evacuation would still be an option. In this case, three options would be available to the Master: return to port, waiting for rescue on board the ship, and evacuating to the life rafts.

This analysis is entirely performance-based. The fire safety engineering team disregarded the requirements of the IMO Code for application of fire test procedures (FTP Code) [4], disregarded the need to use the prescriptive ISO 834 fire curve [5]. The design philosophy is in three steps:

- Calculate the expected worse fire curve in the battery room (i.e. estimate the appropriate natural fire curve)
- Based on this curve, calculate whether the standard passive protection use in a deck with an A60 classification would meet the objective of keeping the temperature rise of the unexposed side of the deck (towards the passenger accommodation) below 40 °C for the entire duration of the calculated fire
- If the objective of keeping the unexposed side of the deck below 40 °C is not met, what thickness should the insulation layer have in order to achieve this performance

This procedure will ensure that the safety objectives 1, 2, 3, and 5 are met for the fire risks 1 to 14 described in Table 3.
It should be noted that this procedure has not been repeated for other rooms or other scenarios on board the ship. A similar philosophy could be applied to achieve the fire safety objectives in the other spaces of the ship.

Appendix A of the present document presents the details of the calculations, together with important limitations and detailed discussions of these limitations. This part focuses solely on the results and their direct interpretation. The calculations of the fire curves were made with the program CFAST [6,7], and the temperature estimates on the unexposed side of the deck were calculated with COMSOL Multiphysics [8].

Battery room model and hypotheses

The battery room is seen as a compartment of dimensions $4 \times 6 \times 1.95$ m^3. The walls are considered made of steel and insulated with mineral wool. The room is fitted with mechanical ventilation, with an air exchange rate of 6 times per hour. The ventilation outlets are assumed to be located at the ceiling level of the compartment, symmetrically along the long side.
A small leakage opening was introduced in the model to represent imperfections in the air tightness of the compartment. For some simulations, the leakage was made larger to model the effect of a fire door left ajar.
The geometry of the compartment for the simulations is presented in Figure 2-1.

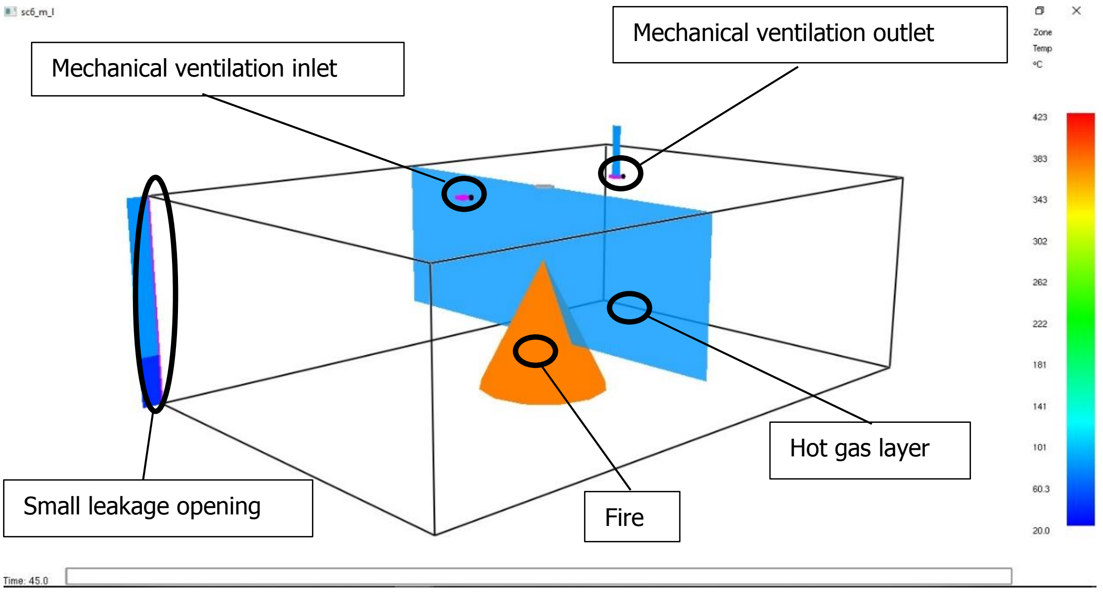

Figure 2-1 – Geometry of the compartment as used in the CFAST models. The visualization is provided by the program Smokeview.

Fire curves

A total of 11 design fires were defined. All have the same fuel load, corresponding to the energy content of the batteries present in the room. The design fires differ in their peak heat release rate (HRR), which represents how the energy is released during burning. Each of the design fires contains sub-scenarios, obtained by changing the fire growth rate and the ventilation conditions. All design fires and their sub-scenarios are presented in Table 4.

Table 4 – Overview of the calculated design fires making the simulation programme

Nr	Peak HRR [kW]	Fire growth rate	Ventilation conditions	Burning area [m²]	Fuel load [MJ]
1	10000	medium	mechanical	1.26	28912
2	10000	Ultra-fast	mechanical	1.26	28912
2-L	10000	Ultra-fast	Large leakage	1.26	28912
2-L+M	10000	Ultra-fast	Mechanical + small leakage	1.26	28912
3	3000	medium	mechanical	1.26	28912
4	3000	Ultra-fast	mechanical	1.26	28912
4-L	3000	Ultra-fast	Large leakage	1.26	28912
4-L+M	3000	Ultra-fast	Mechanical + small leakage	1.26	28912
5	1000	medium	mechanical	1.26	28912
6	1000	Ultra-fast	mechanical	1.26	28912
6-L	1000	Ultra-fast	Large leakage	1.26	28912
6-L+M	1000	Ultra-fast	Mechanical + small leakage	1.26	28912
7	700	Ultra-fast	mechanical	1.26	28912
7-L	700	Ultra-fast	Large leakage	1.26	28912
7-L+M	700	Ultra-fast	Mechanical + small leakage	1.26	28912
8	500	Ultra-fast	mechanical	1.26	28912
8-L	500	Ultra-fast	Large leakage	1.26	28912
8-L+M	500	Ultra-fast	Mechanical + small leakage	1.26	28912
9	200	Ultra-fast	mechanical	1.26	28912
9-L	200	Ultra-fast	Large leakage	1.26	28912
10	100	Ultra-fast	mechanical	1.26	28912
10-L	100	Ultra-fast	Large leakage	1.26	28912
11-L	50	Ultra-fast	Large leakage	1.26	28912
11-L+M	50	Ultra-fast	Mechanical + small leakage	1.26	28912

The fire curves calculated with CFAST are shown in Figure 2-2, Figure 2-3, and Figure 2-4.

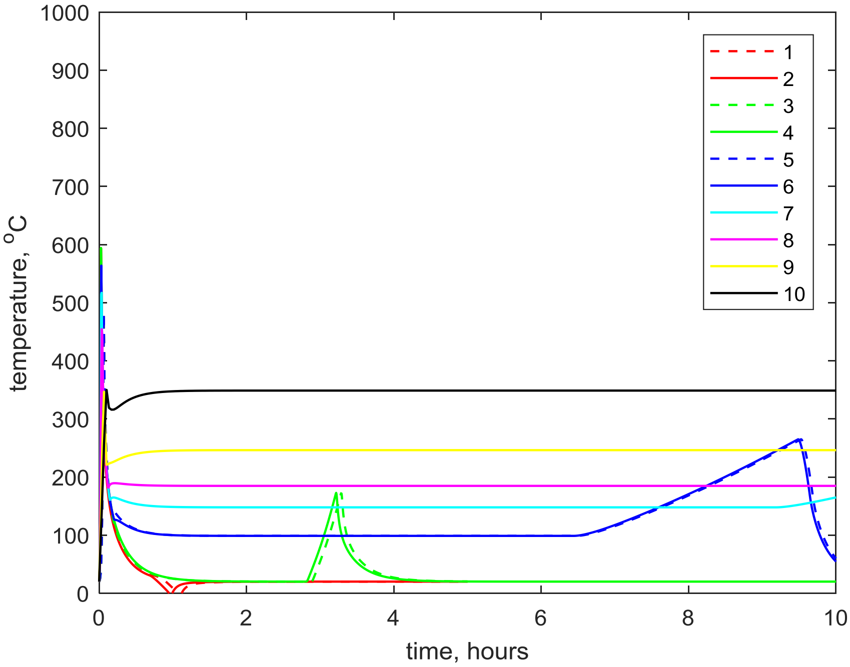

Figure 2-2 – Gas temperature estimation for design fires with mechanical ventilation. The time axis is limited to 10 h for the purpose of clarity, though some of the fires last longer than 10 h.

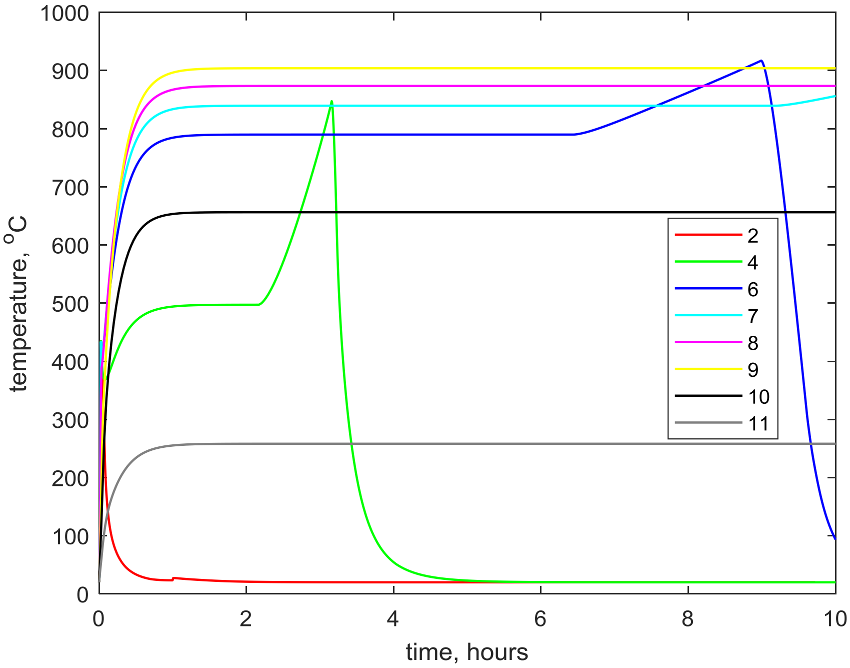

Figure 2-3 – Gas temperature estimation for design fires with large leakage. The time axis is limited to 10 h for the purpose of clarity, though some of the fires last longer than 10 h.

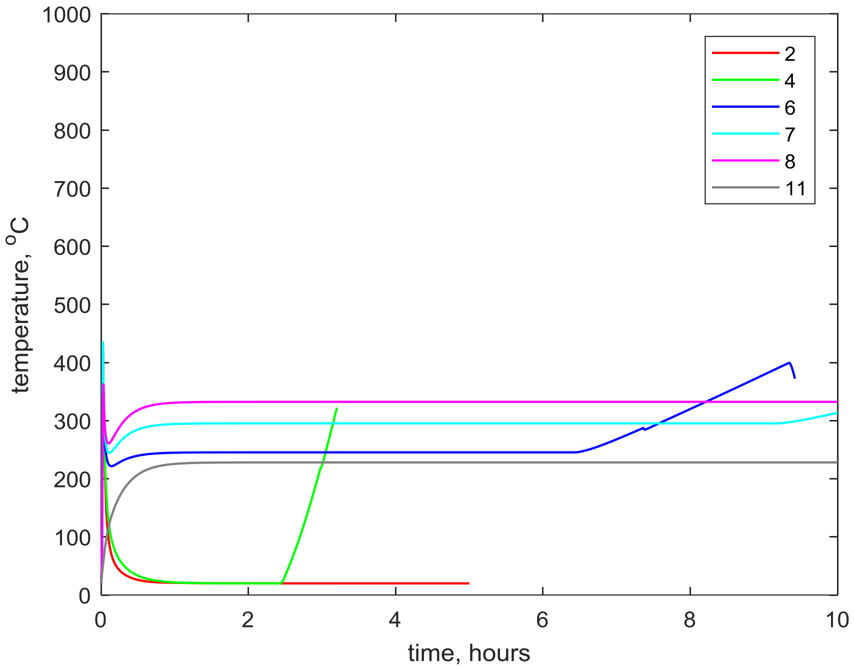

Figure 2-4 – Gas temperature estimation for design fires with mechanical ventilation + small leakage. The time axis is limited to 10 h for the purpose of clarity, though some of the fires last longer than 10 h.

Unexposed surface temperature of the deck

A simple heat transfer model was used on a construction assumed to be a steel deck protected by 50 mm of mineral wool on the exposed side, and a steel sheet of thickness 5 mm was placed on the unexposed side. The analysis was simplified to a one dimensional calculation. The results from the CFAST calculations were used as input to represent the exposure temperatures.
The results of the COMSOL calculations are a relative temperature rise. The results are reported in Table 5, Table 6, and Table 7.

Table 5 – Maximum temperature rise on the unexposed surface of the construction if only mechanical ventilation is assumed

Nr	Peak HRR [kW]	Fire growth rate	Ventilation	Max relative temperature rise on the unexposed side of the deck [°C]
1	10000	medium	mechanical	6
2	10000	Ultra-fast	mechanical	6
3	3000	medium	mechanical	6
4	3000	Ultra-fast	mechanical	7
5	1000	medium	mechanical	19
6	1000	Ultra-fast	mechanical	20
7	700	Ultra-fast	mechanical	22
8	500	Ultra-fast	mechanical	23
9	200	Ultra-fast	mechanical	25
10	100	Ultra-fast	mechanical	35
11	50	Ultra-fast	mechanical	(NA)

Table 6 – Maximum temperatures on the unexposed surface of the construction if large leakage condiotion is assumed

Nr	Peak HRR [kW]	Fire growth rate	Ventilation	Max relative temperature rise on the unexposed side of the deck [°C]
2-L	10000	Ultra-fast	Large leakage	5
4-L	3000	Ultra-fast	Large leakage	87
6-L	1000	Ultra-fast	Large leakage	125
7-L	700	Ultra-fast	Large leakage	127
8-L	500	Ultra-fast	Large leakage	130
9-L	200	Ultra-fast	Large leakage	127
10-L	100	Ultra-fast	Large leakage	79
11-L	50	Ultra-fast	Large leakage	23

Table 7 – Maximum temperatures on the unexposed side of the construction if small leakage + mechanical ventilation condition is assumed

Nr	Peak HRR [kW]	Fire growth rate	Ventilation	Max relative temperature rise on the unexposed side of the deck [°C]
2-M+L	10000	Ultra-fast	Mechanical + small leakage	3
4-L+M	3000	Ultra-fast	Mechanical + small leakage	4
6-L+M	1000	Ultra-fast	Mechanical + small leakage	35
7-L+M	700	Ultra-fast	Mechanical + small leakage	38
8-L+M	500	Ultra-fast	Mechanical + small leakage	39
9-L+M	200	Ultra-fast	Mechanical + small leakage	(NA)
10-L+M	100	Ultra-fast	Mechanical + small leakage	(NA)
11-L+M	50	Ultra-fast	Mechanical + small leakage	20

Discussion of results

Fire curves

The results show that in the present case the ventilation is likely to control the rate of burning. The fire load of the Li-ion batteries is relatively large, but due to the limited ventilation, it is expected not to burn with limited rate and generating relatively low compartment temperatures.

Due to the limited ventilation, it can be expected that the fires self-extinguish due to lack of oxygen and are not capable to re-ignite. It is difficult to establish the extinguishing of the fire, as the model always considers that the combustible pyrolysis gases are produced independently of the external conditions. The uncertainty around extinguishment prediction leads to some very long-lasting design fires. From the perspective of extinguishment, the compartment temperatures are seen to be conservative.

The highest compartment temperatures were calculated in case of a 'large leakage'. The large leakage can represent doors that are not properly closed or if the compartment have significant leakage problems. Such scenario may be very dangerous not only from the perspective of high compartment temperatures, but also because of expected external flaming outside the compartment.

Passive protection
All scenarios with mechanical ventilation alone or small leakage + mechanical ventilation showed positive results in the heat transfer calculations. None of these scenarios shows a temperature rise on the unexposed side of the deck above 39 °C, which is below the target of 40 °C. These calculations include the full duration of the design fires.
This encouraging result indicates that for most fires, the standard A60 protection would suffice to allow passengers to stay in the passenger lounge for the entire duration of a fire in the battery room. The only scenarios where this claim may be invalid concern scenarios where a large leakage would be present, most likely form a door left ajar. This specific point could lead to a functional requirement stating that "it must be ensured that doors of below-deck spaces are closed at all times", which would be achievable with sensors, and would not be a hindrance to operation considering the limited manning situation of the concerned ship.

Final observation
This example showed how some technical solutions can be design to enforce the fire safety objectives stated in Section 1.3. The same approach can be used on all rooms. For other items than passive fire protection, other engineering approaches or focus areas would be investigated.
This example also showed that the requirements of the FTP Code (therefore partially of SOLAS) are not rooted in reality. These requirements use theoretical worst case situations, without guarantee they would actually be a worst case situation. In some cases, it would lead to an overdesigned situation (on the safe side with regards to safety, but not necessarily consistent economically). It might also be that some cases theoretically represented by the FTP Code are not conservative. As a conclusion, the method proposed above could be a way to design safer and cheaper with respect to fire safety at the cost, it is true, of a longer design process.

2.3 Ship scale

This section presents the design points of the qualitative analysis relevant for the ship as a whole, and are not specific to a room. They nonetheless are an integral part of the chain of events proposed in Table 1.

#2 – Fire is detected
The ship and the on-board systems always handle fire detection. For redundancy purposes, at least two independent systems are installed.

#3 – The Master is presented with the alarm
Detection with one single system (see **#2**) sends a pre-alarm to the master, so he knows a problem may come. As soon as a second detection means catches the fire, the system confirms detection and sends a real alarm.
The alarm can be delivered as a sound alarm, a visual alarm (blinking lights in the bridge), and an on-screen alarm.
<u>Technical reasons why the Master is not presented with the alarm:</u>

- Signal doesn't reach due to disconnected/faulty wire (mitigation: this issue should have its own alarm and send an error message to the main display before a fire would occur)
- Visualization frozen (mitigation: no visibility on ship systems, failure is not fire-related so it should be detected and fixed before a fire breaks out)
- Lack of power between input and output (mitigation: emergency power available due to 2 battery rooms + UPS in bridge. The 2 battery rooms are independent, one working as emergency to the other. The battery capacity is also dimensioned to be recharged when max 60% is used up.)

- The cues are not accessible (mitigation: we have at least a visual and a sound system, which should be independently wired. If there is a bathroom in the bridge, alarm should be displayed there as well.)

Human-related reasons why the Master is not presented with the alarm:
- Master is incapacitated (mitigation: presence check either by compulsory regular communication to shore or automatic system)
- Master is in the bathroom with headphones (mitigation: alarm in the bathroom with light cues)

#4 – Confirmation of detection

The strategy is the same for all rooms. The system handles detection confirmation, meaning that at least two independent systems must detect the fire. For this reason, a minimum of 3 independent systems must be found in each room. The specific rooms have specific set-ups according to their content.
All systems should detect a fire at least as fast as the standard detection solution for the given room. This measure ensures a swift response of the ship to the fire event.
The Master could also confirm detection of the fire, but it is not expected to be his role. Due to the choice of systems installed, the ship will most likely be faster than the Master to perform confirmation.

#5 – Passengers are informed of a "problem" and instructed to proceed to the muster station

The Master informs the passengers. Alternatively, the first message could be an automatic message, sounding like a real person speaking, telling that the Master will soon get in touch.
Technical reasons why this cannot be done:
- PA fault (mitigation: should be checked regularly, e.g. at every docking. If it doesn't work, don't sail)
- Poor sound quality (mitigation: high quality audio with sufficient sound power, not sounding like regular train or airport PA)

Human-related reasons why this cannot be done:
- Incapacitated Master, not fire related (mitigation: see **#3**)
- Incapacitated Master due to the fire – no mitigation found for this situation. This should be avoided. Alternatively, a specifically focused analysis of that topic should show that the risk is ALARP.
- Uncertainty about the situation (mitigation: the Master's primary role on board is to retain situational awareness. The ship handles the other fire-related and navigation-related tasks.)

What if passengers are directed to the wrong muster station:
This relies on the Master's situational awareness. In the present case of a fire below deck, both muster stations can be used. In the case where only one of them is usable, the Master should know which one. This situation is not different from that of a standard ferry, so standard rules should apply.

#6 – Distress message is sent to shore

Message is sent to JRCC. In the case of this specific ferry, fire events are always treated as highly serious given the situation of only 1 crew for 150 passengers. One of the Master's main roles is to establish communication with shore, so this procedure will receive priority from him/her.
Message is sent to shore via:
- VHF – Master's responsibility to contact shore support
- VHF – digital message, sent automatically by the ship upon confirmation of detection
- Call 112 and the call is directed to JRCC.

Technical reasons why this is not possible:

- Automatic message: detection signal not received by the system (see **#3**)
- Automatic message: detection confirmation does not occur (see **#2**, **#3**, **#4**)
- VHF does not function (mitigation: this is highly unlikely, but there is also cell signal in the specific area of operation of the ship)

<u>Human-related reasons why this is not possible:</u>

- Master is incapacitated (mitigation: the ship sends a message automatically)

#7 – Return to port initiated

Return to port is systematically initiated by the ship, as it is part of the fire safety strategy that safe return to port should be ensured. If propulsion means are not available any more, evacuation is considered according to **#11**.

<u>From Fanø to Esbjerg:</u>

Strategy is to keep sailing to Esbjerg. As the route is short and Esbjerg is a large harbour with excellent support facilities, it makes sense to keep sailing the intended route. Docking may be changed from standard procedure, which is detailed in **#10**.

<u>From Esbjerg to Fanø:</u>

- Strategy is to sail to Fanø to disembark passengers.
- If the ship is at less than 50% towards Fanø, it could be possible to turn around and sail back to Esbjerg, depending on how quickly the ship can turn around.

<u>What if the ship cannot return to port:</u>

- Scenario 1: wait for tug boat. This situation is conditioned to monitoring the development of the fire event (see **#9**) and if conditions are tenable, passengers and crew should remain on board and wait.
- Scenario 2: evacuation using MES. When the situation is not tenable any longer, evacuation is detailed in **#11**.

#8 – Firefighting initiated

Each room has its own most appropriate system.

The strategy is nevertheless the same for each room. Firefighting is initiated as soon as detection is confirmed, in an attempt to maximise the chance to control the fire. As a result, the action to initiate firefighting is taken by the system.

<u>Dismissible automatic firefighting process:</u>

As a safety measure, the system presents the Master with a possibility to dismiss the automatic firefighting process. The Master could use this option if there is uncertainty on the presence of people in the room. This could also cover the case where the occurrence of fire is actually doubtful and the Master fears damaging equipment for no good reason.

<u>Passengers:</u>

Passengers should/must escape from the lounge before active firefighting systems are deployed.

#9 – Continuous communication with passengers and shore support

The objective is to keep passenger calm, make them do what they have to do, and coordinate rescue efforts with shore.

The Master communicates with the passengers using the PA. The PA is assumed to be a robust system industry-wide. If the risk control options stated in **#5** are implemented, it could be said that the risk concerning the PA are assumed to be ALARP.

The Master communicates with the shore (JRCC or other) via VHF or cell phone. The cell phone could use both regular phone signal and satellite signal.

It is agreed in the design team that passengers should be addressed every few minutes in order to retain a high degree of trust, and to make them feel that the situation is being handled. To increase the chances of success, the pre-ride situation has been considered as a preparation period for the passengers (see Appendix 2 and Concluding report).

#10 – Docking ship at ferry terminal

Navigation in the harbour is unsure at this point. In case of fire on board, the ship will most likely be directed to another area of the harbour than the ferry terminal. This raises the question of automatic navigation in the harbour, compared to manual steering. In turns, it raises the concern of automatic mooring and the need for shore support in this operation.
The need for manual steering in the harbour area requires that the Master is not incapacitated.
If the bow opening does not work, people are directed to the MES.

#11 – Evacuate passengers

What should be happening to justify evacuation in the case of fire:

- Fire spreads to adjacent room – it is considered that fire is out of control
- Collision + fire = immediate evacuation
- Explosion + fire = immediate evacuation
- Temperature monitoring in the floor of the passenger lounge rises above an acceptable threshold

<u>Disembarking at port:</u>

- Possible when the fire is not on deck
- Circulation on the deck must be ensured, difficult during busy days with bikes on the front deck (mitigation: marked areas for bike parking, enforcement of bike policy)

<u>Emergency evacuation:</u>

- MES is triggered from the bridge, with automatic deployment
- Passengers help themselves onto the MES
- There is one MES on each side, both with 100% capacity
- The design team suggests treating the passenger lounge and the front open deck as two separate fire zones, each with its own MES. The topic of reliability of the MES should be addressed, as there would not be redundancy of the evacuation system in each fire zone. The argument of additional fire barriers could be used instead (early detection, early trigger of suppression system, dimensioning of the passive protection to make the ship its own best life boat…)

3 Fire safety strategy

3.1 Hypotheses

The development of the fire safety strategy requires the formulation of several hypotheses. They frame the context of the work, and limit its applicability.

- The ship is operated by 1 (one) single crew member, having the function and authority of Master
- There is no control centre at shore – remote navigation is not available
- “Autonomy” is detailed only for fire safety
- The systems on board operate navigation without needed interaction with the Master
- The described level of autonomy is the minimum level compatible with what a single person can do

3.2 Who does what?

The level of autonomy chosen in this project is not formalised. Several classification societies proposed scales of autonomy [4,5], which are adapted to and usable for topics such as situational awareness, ship steering etc. Following a specific level of autonomy would be an attempt to label a performance level, to set an objective without any link to the fire safety objectives. Instead of aiming for a given level of autonomy, the project team focused on providing the necessary level of “autonomous fire safety” to ensure safe operation and safe management of a fire situation. Without any particular attempt to automatize fire safety, some aspects of it are fairly independent from human input already today (e.g. fire detection).

In the context of the present ship, the Master would find him/herself on board with a maximum of 150 passengers. Based on the work on human factors detailed in Appendix 2, passengers referred on multiple occasions to the need to communicate and be informed of the situation. They would feel safer with the possibility to talk to someone about the situation. This tends to indicate that the Master needs to be responsible for the passenger, the communication with them, and the management of their reactions to ensure that they would act in the intended way. Additionally, the Master needs to communicate with the shore to ensure the situational understanding of first responders and rescue. Together, these two tasks appear to be enough work for a single person.

As a corollary, other vital functions need to be performed by the ship. This fosters the idea that the ship and the Master are two members of a team, each with a specific function within the team, to achieve the safety objectives. This also means that the two functions should not overlap. A delicate point to consider is the level of control or verification that the Master should have on the operation of the ship and its systems.

The ship (to be understood here as the systems present on board the ship) needs to care for the navigation functions and the fire safety functions. It implies that the technical functions should be technology-based to the largest possible extent, so that a system could handle them. The more technical functions are handled by the ship, the less have to be under the Master’s role.

As a conclusion of the split of roles within the Master-ship team, the project team suggests:

- The Master handles communication with the passengers and shore
- The ship handles navigation and fire safety systems

The Master retains the decision power, which means that the decision to evacuate the ship remains his/hers.

3.2.1 The Master

The role of the Master is particularly oriented towards communication, with the passengers and with the shore for crisis management.

- Notifies passengers of an incident
- Keeps communication flowing with passengers every few minutes, reassures them, informs them of the development of events
- Sends distress message to shore via VHF
- Keeps communication with shore, and coordinates rescue or return to port
- Has final decision on return to port or staying put (can cancel the ship's initiative to return to port)
- Has final decision on evacuation
- Prepares passengers for evacuation
- Asks system to deploy Marine Evacuation System (MES)
- Orders evacuation, coordinates it, evacuates him/herself
- If docking, coordinates mooring, shore assistance, and disembarking

Additionally, the Master should retain situational awareness at all times by monitoring information from the system, including the effect and efficiency of firefighting.

The Master should trust the system and the information the system reports. Checking possibilities are provided, in order to increase redundancy and create the synergy needed for teamwork.

The main role of the Master with respect to direct mitigation of a fire situation is the possibility to dismiss and cancel automatic firefighting, and to trigger firefighting manually.

3.2.2 The ship

The role of the ship is particularly oriented towards handling the fire itself, on a technical level.

- Detects fire and confirms detection
- Notifies Master that fire is detected and proposes to dismiss automatic firefighting
- Displays monitoring options (CCTV, temperature recordings…)
- Initiates firefighting (closes ventilation dampers, sends dismissible firefighting notification, triggers active systems, self-check of firefighting system release, monitors effects of firefighting)
- Sends digital distress signal to shore and notifies Master
- If propulsion is available, initiates return to port and notifies Master. If propulsion is not available, notifies Master
- Deploys required MES when instructed

3.3 Summary of the fire safety strategy

This section summarises the work presented above, highlighting the mainlines of the fire safety strategy for the small autonomous ferry at hand. The fire safety strategy lies on the following principles:

- Separation of roles between Master and ship to minimise response time and to simplify procedures
- Synergy between Master and ship to create a team which can check itself, increasing redundancy
- Early detection
- Fast decision making by automating actions, leading to quick response and early treatment of the fire issue (maximises the chance to control the fire and contain it to the compartment of origin)

- Keeping passengers on board to avoid potentially risky evacuation, which translates into the use of two muster stations and fire safety engineering calculations for passive protection. The level of redundancy is therefore raised with more risk control options in place.
- High level of redundancy of fire safety systems
- Fire safety design integrates the operational setup of the ship and accounts for passenger behaviour.

3.4 Functional requirements

The main functional requirements highlighted in this work are:

- Separation of functions between Master and ship
- Use of two muster stations
- Use of MES in each muster station
- Condition the start of the ship's propulsion system to the assurance that no one is present in the below-deck spaces.

3.5 Challenges

The challenges this refers to can be of several kinds:

- Technical challenges
- Legal challenges
- Methodological challenges
- Technological challenges

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5 Appendix A – Full details of CFAST and COMSOL calculations for the battery room

5.1 Problem description and solution procedure

The task is to assess the insulation performance of fire separating elements (a deck) on a ferry. The assessment focuses on one of the battery rooms containing Li-ion batteries. The batteries is a potential item to ignite and it has extensive fuel load.
This report presents an initial assessment of the expected fire exposure conditions and thermal response of the separating elements.

The solution procedure is based on fire and heat transfer modelling. Figure 5-1 presents the procedure.

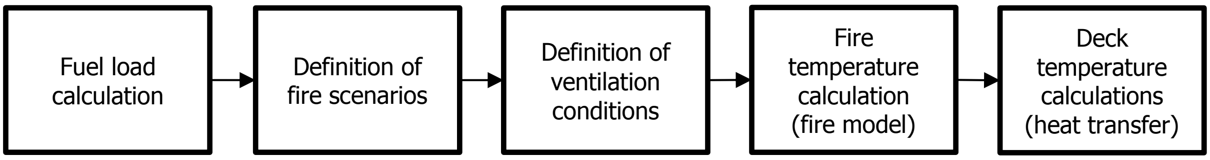

Figure 5-1 – Solution procedure

5.2 Choice of modelling tools

Compartment temperatures were calculated with two zone fire model CFAST version 7.3.0, developed by National Institute of Standards and technology NIST [6]. CFAST calculates an average temperatures in two zones in the compartment: hot layer (smoke layer at the upper zone of the compartment) and cold layer (zone close to the floor level, that typically have lower temperature). For the purpose of this report, the hot layer is of interest and will be referred to as the compartment temperature. CFAST validation have been done for a relatively similar scenario - The Factory Mutual and Sandia National Laboratories (FM/SNL) test series consists of 25 compartment fire experiments conducted in 1985 for the U.S. Nuclear Regulatory Commission (NRC) by Factory Mutual Research Corporation (FMRC), under the direction of Sandia National Laboratories (SNL). These test series will be referred to as FM/SNL test series. FM/SNL tests included Peak Heat release rated (HRR) from 500 to 2000 kW and mechanical ventilation rates from 1 to 10 Air Changes per hour. CFAST showed overall good agreement, however some of the cases approximately up to 70 % underestimations of the hot gas layer temperatures were observed [7].

The separating elements temperatures were calculated by heat conduction model with finite element method in programme Comsol Multiphysics [8].

5.3 Compartment description and hypotheses

See Section 2.2.2.

5.4 Definition of design fires

The definition of design fires consist of assessment of the fuel load, assessment of fire growth rate, assessment of maximum rate of heat release and assessment of the decay phase. The duration of fire is a function of all of the parameters mentioned prior.

Fuel load

It was assumed that the Li-ion batteries is the only fuel source in the compartment. Two battery packs per compartment are expected. The battery components with respective mass fractions are presented in Table 8.

According to the information from the client a standard forced air cooled battery pack of 1550 kg and dimensions in vertical arrangement are 2200 × 870 × 710 mm3. The standard battery pack consist of several EV type batteries. The estimations of the total fuel load is presented in **Fire growth rate**

The growth rate in this case is defined as generic t2 model, where the HRR is defined as a function of time.

$$\dot{Q} = \alpha t^2$$

Fire growth rate α (kW/s^3) define how fast the fire will grow to the peak heat release rate. The fire growth rate for the specific Li ion batteries is unknown; however, the experience shows that the fire development process in this case is extremely fast.

In this study two fire growth rates were investigated [9]:

- Medium α=0.012 kW/s^3 which is characteristic for solid a wood furniture and
- Ultra-fast fire growth rate α=0.188 kW/s^3 which is characteristic for high stacked plastic materials

Peak heat release rate

Wide range of peak HRR have been investigated, starting from 10000 kW down to 50 kW. This is due to limitations of fire modelling to determine the material burning with sufficient accuracy, that a sensitivity study of the assumptions should be made.

Decay phase

The decay phase of HRR was assumed to be linear and to begin when 80 % of fuel is consumed [9].

Table 9.

Table 8 – Material inventories for HEV, PHEV, and EV.

Component	Percent Mass		
	HEV (%)	PHEV (%)	EV (%)
$LiMn_2O_4$	27	28	33
Graphite/carbon	12	12	15
Binder	2.1	2.1	2.5
Copper	13	15	11
Wrought aluminum	24	23	19
$LiPF_6$	1.5	1.7	1.8
EC	4.4	4.9	5.3
DMC	4.4	4.9	5.3
PP	2.0	2.2	1.7
PE	0.26	0.40	0.29
PET	2.2	1.7	1.2
Steel	2.8	1.9	1.4
Thermal insulation	0.43	0.33	0.34
Glycol	2.3	1.3	1.0
Electronic parts	1.5	0.9	1.1
Total battery mass (lb)	41	196	463

Fire growth rate

The growth rate in this case is defined as generic t2 model, where the HRR is defined as a function of time.

$$\dot{Q} = \alpha t^2$$

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Peak heat release rate

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Decay phase

The decay phase of HRR was assumed to be linear and to begin when 80 % of fuel is consumed [9].

Table 9 – Fuel load calculation

Component	Heat of combustion (MJ/kg)	Mass Per battery (kg)	Fuel load per battery (MJ)
LiMn2O4	0	69.304	0.000
Graphite	32	31.502	1008.063
Binder	31	5.250	162.760
Cooper	0	23.101	0.000
Wrought aluminum	0	39.902	0.000
LiPF6	0	3.780	0.000
Ethylene Carbonate	13.3	11.131	148.038
Dimethyl carbonate	23	11.131	256.006
Poly Propylene	43.3	3.570	154.591
Polyethylene	43.3	0.609	26.371
Polyethylene terephthal	23.2	2.520	58.468
Steel	0	2.940	0.000
thermal insulation	0	0.714	0.000
glycol	24.2	2.100	50.823
Electronics parts	39.9	2.310	92.175
Total		209.866	1957.295
Fuel load per kg of battery (MJ)			9.326
Fuel load per two standard 1550 kg battery packs (MJ)			28912

Definition of ventilation conditions

There are no windows in the compartment. Forced mechanical ventilation ensures the air exchange of 6 times per hour in the compartment. There are no more details regarding this ventilation so the following assumptions have been made:

- inflow is ensured through one single opening at the ceiling level. The opening diameter is 10 cm;
- outflow is ensured through one single opening at the ceiling level. The opening diameter is 10 cm;
- the ventilation openings are placed symmetrically along the longest edge of the compartment. It results 2 m away from the short wall of the compartment;
- air exchange of 6 times per hour result in volumetric flow rate 0.078 m^3/s;
- The ventilation drop off occurs if there is 200 Pa counter pressure and after 300 Pa counter pressure the mechanical ventilation drops to 0.

In some fire scenarios, it was assumed that the mechanical ventilation keeps working during the fire. In others, it is assumed that the mechanical ventilation is turned off. If the room would be completely air tight, it is expected that the fire would not manage to develop to as large size as if there would be some air exchange. Hence air leakages are included in some of the calculations as a conservative approach due to uncertain air-tightness of the compartment. One narrow 5 cm wide vertical opening was introduced from the floor level up to ceiling and referred in this report as 'large leakage'. This ventilation condition represent e.g. an assumption that the door to the compartment is not properly closed. A different ventilation conditions included 1 cm wide vertical opening representing some minor air leakage between the bulkheads/deck constructions. The overview of assumed ventilation conditions are presented in Table 10.

Table 10 – Definition of ventilation conditions

Notation	Description
Mechanical	Forced air exchange 6 times per hour
Large leakage	5 cm wide opening over the height of the compartment. Resulting in 0.0975 m^2 opening area or 0.25% or the total wall area
Small leakage	1 cm wide opening over the height of the compartment. Resulting in 0.0195 m^2 opening area or 0.05% or the total wall area

Resulting design fires

The resulting design fires are given in Table 4.

Model inputs

Some of the assumptions used in the compartment temperature calculation model (CFAST) are listed below:

- All compartment boundaries are assumed to have thermal properties similar to stone wool properties. Density was assumed 90 kg/m^3, Thermal conductivity 0.1 W/m/K, Specific heat capacity was assumed 900 J/kg/K, emissivity was assumed 0.9, thickness was assumed 5 cm;
- Begin drop off for the mechanical ventilation was assumed at 200 Pa and zero flow was assumed at 300 Pa;
- Burning fuel was assumed as Propane C3H8. CO yield was assumed 0.008 and soot yield was assumed 0.015, HCN yield was assumed to be 0. It is expected that these parameters would only influence the chemical composition of the hot and cold layers, but would not have a significant impact to the temperature estimates
- Heat of combustion was assumed 50 MJ/kg$_{fuel}$. Radiative fraction of HRR was assumed 0.35;
- Interior humidity was assumed 50%;

5.5 Deck temperature calculations

Model input

Heat transfer analysis was done assuming stone wool/steel deck construction exposed to gas temperatures as calculated with programme CFAST. Stone wool (5 cm) was located on the exposed side and steel sheet (0.5 cm) was placed on the unexposed surface of the construction. One-dimensional analysis was done.

A defined temperature boundary condition was applied to the exposed surface. Combined radiation and convection boundary condition was applied on the unexposed surface:

$$\dot{q}''_{in} = \varepsilon\sigma\left({T_{amb}}^4 - {T_s}^4\right) + \mathrm{h}(T_{amb} - T_s)$$

Where $\dot{q}''_{in}$ is the heat flux from the surface, ε is the emisivity of steel deck (=0.9), σ is the Stefan-Boltzmann constant (=5.6704 × 10^{-8} W/(m^2·K^4)), T_{amb} is the air temperature on the unexposed side (=293 K), T_s is the surface temperature as calculated by Comsol Multophysics model (K), h is the convective heat transfer coefficient (=4 W/m^2/K).

Thermal properties of carbon steel were assumed as given in BS EN 1993-1-2:2005 [10]. Stone wool density was assumed 90 kg/m^3, specific heat capacity 840 J/kg/K. Stone wool thermal conductivity was assumed as presented in Figure 5-2.

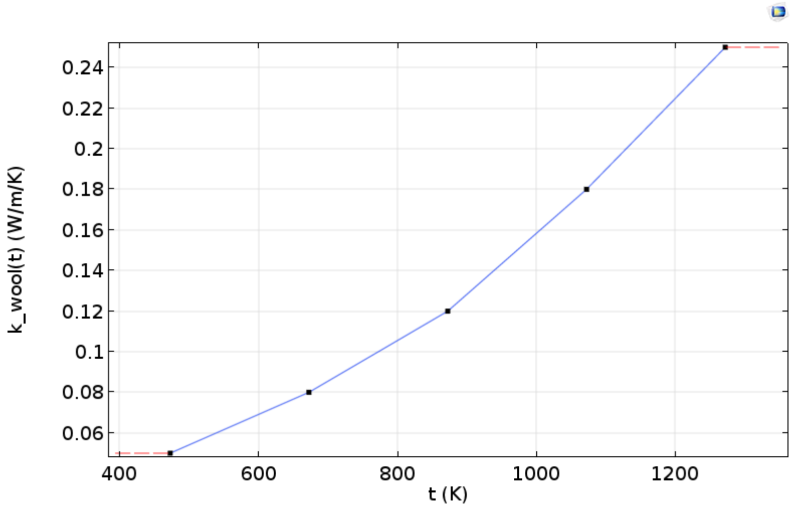

Figure 5-2 – Thermal conductivity of stone wool as used in COMSOL simulations

5.6 Addition to the discussion from Section 2.2.2

This section covers the points of uncertainty towards the design procedure documented herein.

- Lack of consideration of local heating at the early stages of the fire

Large number of simulations were performed with a two-zone model. Two-zone model calculates average temperatures compartment temperatures. Localized heat exposures however are not considered in this report and requires more detailed analysis. Locally higher heat exposures are expected due to the direct flame impingement to some part of the construction. It could be of most concern in the early stages of fire, before the fire becomes ventilation controlled. It is possible that the local exposure may be so severe that it results in melting of the stone wool.

- Risk of the external flaming

It can be concluded from the calculations that ventilation controlled fires are expected in the compartment. In such conditions, there is a risk that the combustible pyrolysis gases will leave the compartment through the openings (either mechanical ventilation openings or leakage openings) and will burn outside the compartment. This could also occur in the ventilation ducts, which hence should be protected in a sufficient way not to allow fire and smoke spread to other compartments.

- Risk of a backdraft

In ventilation-limited fires a large build-up of combustible gases is expected in the compartment. These combustible gases will only burn with limited rate in the compartment. However if during the fire an opening is introduced in the compartment a backdraft (high rate combustion event) occurrence is likely. This may occur upon the intervention of fire fighters, if a door is opened by accident or if any of the separating elements lose its integrity.

- Uncertainties in performance of stone wool in extensively long exposures

Typical fire resistance tests are of duration of 30 minutes to 2 hours. In the present case the fire scenarios are of many hours. Despite relatively low compartment temperatures, due to the long exposure duration the performance of the deck construction may differ from that observed in a standard dire resistance test. It included possible degradation of stone wool and mechanical detachment of the steel deck construction. In the presented calculations, it is assumed that the stone wool is attached to steel deck with perfect thermal contact at all times.

6 Appendix B – Room-by-room analysis for other spaces of the ship

This appendix reports only the elements relevant to a given room.

PASSENGER LOUNGE

#1 – Fire occurs – what scenario is considered

Identified ignition sources at passenger lounge: Lights – due to loose connections, faulty fixtures, or vibrations (recommend LED to mitigate this). Personal electronic device – ignition would most likely be due to a battery failure like seen on Samsung Note 7 and electric smoking devices (e-cigarettes). Arson – Can happen in the passenger lounge, either by igniting something in the lounge like a trashcan or by bringing an external fuel source (most likely a liquid). Fireworks – This scenario seems somewhat unlikely, but perhaps during peak season at the end of December. Ignition happens due to friction, spontaneously, or due to moisture.

#2 – Fire is detected

The system is envisioned as similar to that of the propulsion room.
In addition, there will most likely be passengers present in the lounge during regular voyages; these would in most likelihood observe smoke or flames, and should therefore be able to notify the Master at the bridge through an intercom system or callpoint (direct to system). Such as system should probably be present regardless for security reasons. As a result, detection and its confirmation can be expected simultaneous and quick in this room.

#3 – The Master is presented with the alarm

This point is relevant for all rooms and is detailed in Section 2.3.

#4- Confirmation of detection

The same set-up as for the propulsion room is envisioned in the passenger accommodation. Additionally, there is a certain likelihood that the passengers will act upon seeing the fire in the room they find themselves. This will serve as one more possibility of detection confirmation.

#5 – Passengers are informed of a "problem" and instructed to proceed to the muster station

The primary muster station is the passenger lounge. This is not a viable option in the case of a fire in said lounge. A secondary muster station is needed in this case to ensure evacuation (particularly in regards to the combustible materials used for linings and furniture which can disable passengers and jeopardise evacuation).
Potential other muster stations would be the open front deck and the top deck on the bridge level. The front deck offers easy access to evacuation when the vessel is docked. Likewise, one MES will be accessible from the front open deck. The issue with the front open deck is in all likelihood a lack of space. If the deck is full of bikes and scooters it might not be an ideal muster station.
The top deck offers more space with no bikes or scooters stored nearby. Additionally, the master will be able to visually see the passengers trough the bridge windows. However, the top deck is isolated from the MES systems which will add significantly to potential evacuation times. Additionally, the top deck might not be accessible for physically challenged or elderly passengers.

Proposed solution (1) is to use the open front deck as the secondary muster station due to accessibility and close proximity to the MES. However, measures must be taken to ensure sufficient space for all passengers to stand on the open deck without being hindered by bicycles or other objects.

- Floor markings of "no parking" space on open front deck

- Move one MES outside (port side) under the stairs
- Fire rated doors between passenger lounge and open front deck (rating dependent on FSE conclusions, alternatively follow notice D).
- Fire rated glass for windows and doors (two fire zones)
- 100% life jacket capacity in both fire zones (this is not an ideal recommendation nor an economically viable idea. Other engineering solution recommended).
- MES could be completely removed in this solution by using fire safety engineering in the spirit of the example given in Section 2.2.2.
- Door to aft deck is to be fire rated

Proposed solution (2). Whole deck is one fire zone. Strategy is immediate evacuation if fire is confirmed anywhere on the deck. MES are compulsory. This complies with notice D on life jackets; however, we are in doubt as to practicality of this.

Four locations for reaching the muster station (open front deck) in this scenario.
- People on the front deck are instructed to stay
- People on the top deck are instructed to use the staircase in the front
- People inside the passenger lounge are instructed to use nearest exit. This will lead some to the aft deck.
- People on the open aft deck are instructed to use the ladder to the open top deck and then proceed using the staircase.

#6 – Distress message is sent to shore
This point is relevant for all rooms and is detailed in Section 2.3.

#7 – Return to port initiated
This point is relevant for all rooms and is detailed in Section 2.3.

#8 – Firefighting initiated
Ventilation is initiated to clear the room of smoke (circulation from this area should be closed to ensure smoke doesn't spread through the ventilation system to the rest of the ship). Additionally active firefighting should be activated. The focus here is that passengers might still be present in the room, therefore ruling out CO_2. There are no vital components in this room to be damaged by water or powder, so one of these methods would be more ideal. Sprinkler or water mist.
Fuel amount in the room is uncertain. However, there will be furniture, wall panels etc. present at all times. In addition, there will be a variable amount of passenger belongings that will not be fire retarded. These include clothing, newspapers, magazines, electronics, and luggage. Due to the relatively high amount of fuel and the close proximity to passengers, early detection and firefighting is vital in this room. The focus has been on solutions which can be used in combination with passenger presence in the room.
Additionally, the PA should be of suitable IP rating to function in the presence of water so that potentially present passengers can still hear the Master.

#9 – Continuous communication with passengers and shore support
This point is relevant for all rooms and is detailed in Section 2.3.

#10 – Dock ship at ferry terminal
This point is relevant for all rooms and is detailed in Section 2.3.

#11 – Evacuate passengers
This point is relevant for all rooms and is detailed in Section 2.3.

This specific situation calls for evacuation from the open front deck, meaning that all passengers must be directed to the open front deck. This is the responsibility of the Master in the evacuation situation.
The life rafts deployed by the MES system are made of combustible material, though they could be fire retarded. To avoid any risk of fire spread to the life rafts during the evacuation procedure, at least the first two windows of the passenger accommodation after the life rafts must be of fire rated glass.

OPEN FRONT DECK
#1 – Fire occurs – what scenario is considered
Identified ignition sources at the open front deck: Car (Ambulance) - This is a special case scenario and passenger amount will be limited to the driver and assistant in the vehicle. No other passenger should be present. Lights – due to loose connections, faulty fixtures, or vibrations. Personal electronic device – ignition would most likely be due to a battery failure like seen on Samsung Note 7 and electric smoking devices (e-cigarettes). Arson – Can happen at the open deck, either by igniting something in the lounge like a trashcan or by bringing an external fuel source (most likely a liquid). Fireworks – This scenario seems somewhat unlikely, but perhaps during peak season at the end of December. Ignition happens due to friction, spontaneously, or due to moisture. Combustion engines (scooters and motorbikes) – Malfunction, leaking fuel, hot surface etc. Electric engines (E-bikes) – Battery failure or short circuit.

There are potentially high amounts of ignition sources and fuel present at the open front deck. Potential fuel sources: Batteries, Gasoline, Plastics, Rubber (tyres, gaskets, fenders), Paints and Coatings, Rope and Mooring equipment.

#2 – Fire is detected
CCTV is an obvious choice to cover visual detection. In addition, there is a small amount of roofing covering parts of the deck that could hold temperature and or smoke detectors.
It appears from the GA that the master will have visual on the parts of the deck that is not covered by the roof.
We cannot rely on the master to make the visual detection. The ship must be able to autonomously detect and confirm a fire alarm.
The detector is assumed to be a traditional detection system, or an aspiration system
If it doesn't detect, we need a backup system. The backup system is a different type of system, and is independent from the first one. Its input is displayed on the same visualization system in the bridge.
The detection can be the same system as is used in other rooms i.e. smoke detector and a temperature sensor. Additional detection methods will be via CCTV.
In addition, there will most likely be passengers present on the deck or in the lounge during regular voyages; these would in most likelihood observe smoke or flames, and should therefore be able to notify the Master at the bridge through an intercom system. Such as system should probably be present regardless for security reasons.

#3 – The Master is presented with the alarm
This point is relevant for all rooms and is detailed in Section 2.3.

#4- Confirmation of detection
The discussion relates to **#2**.

#5 – Passengers are informed of a "problem" and instructed to proceed to the muster station

Passengers must be informed of the event and directed to the passenger lounge. Passengers on the open top deck are to be directed to use the staircase to the open aft deck as we cannot be certain that they can go through the open front deck to reach the passenger lounge.
If we go with the two fire zone strategy – passengers should be able to remain safe within the passenger lounge.

#6 – Distress message is sent to shore

This point is relevant for all rooms and is detailed in Section 2.3.

#7 – Return to port initiated

This point is relevant for all rooms and is detailed in Section 2.3.

#8 – Firefighting initiated

The discussion is still open. However, this is an outdoors space with limited fuel and limited possibilities of fire spread. With appropriate engineering justification, the strategy could be to let the fire die out.

#9 – Continuous communication with passengers and shore support

This point is relevant for all rooms and is detailed in Section 2.3.

#10 – Dock ship at ferry terminal

This point is relevant for all rooms and is detailed in Section 2.3.

#11 – Evacuate passengers

This point is relevant for all rooms and is detailed in Section 2.3.
This specific situation calls for evacuation from the passenger lounge. This is a closed space with fire protection features so in this scenario it may be the safest place to be, compared to evacuation in the MES. The fire on the open front deck could generate particles igniting the life raft, though less likely due to the small roof element placed above the bike parking on the side of the MES (starboard side).

OPEN TOP DECK

#1 – Fire occurs – what scenario is considered

Identified ignition sources at the open top deck: Personal electronic device – ignition would most likely be due to a battery failure like seen on Samsung Note 7 and electric smoking devices (e-cigarettes). Arson – Can happen at the open top deck, either by igniting something in the lounge like a trashcan or by bringing an external fuel source (most likely a liquid). Fireworks – This scenario seems somewhat unlikely, but perhaps during peak season at the end of December. Ignition happens due to friction, spontaneously, or due to moisture.
Fuel sources are primarily furniture (either wood or plastic), and litter from trashcans.

#2 – Fire is detected

The detection situation is similar to the open front deck.

#3 – The Master is presented with the alarm

This point is relevant for all rooms and is detailed in Section 2.3.

#4- Confirmation of detection

The discussion relates to **#2**.

#5 – Passengers are informed of a "problem" and instructed to proceed to the muster station
Passengers must be informed of the event and directed to the passenger lounge. Passengers can use both the normal staircase to the front deck and through to the passenger lounge, or the ladder at the aft deck.
If we go with the two fire zone strategy – passengers should be able to remain safe within the passenger lounge.

#6 – Distress message is sent to shore
This point is relevant for all rooms and is detailed in Section 2.3.

#7 – Return to port initiated
This point is relevant for all rooms and is detailed in Section 2.3.

#8 – Firefighting initiated
The discussion is still open. However, this is an outdoors space with limited fuel and limited possibilities of fire spread. Two strategies could be followed, which are manual firefighting from the Master or letting the fire die out. The first strategy challenges the assumption of split responsibility between Master and ship, and places the Master at stake. The second strategy requires fire safety engineering to show that the bridge is kept safe and operational at all times.

#9 – Continuous communication with passengers and shore support
This point is relevant for all rooms and is detailed in Section 2.3.

#10 – Dock ship at ferry terminal
This point is relevant for all rooms and is detailed in Section 2.3.

#11 – Evacuate passengers
This point is relevant for all rooms and is detailed in Section 2.3.
This specific situation calls for evacuation from the passenger lounge. This is a closed space with fire protection features so in this scenario it may be the safest place to be, compared to evacuation in the MES.

BATTERY ROOM
#1 – Fire occurs – what scenario is considered
A fire is considered either in a battery rack or at a cable connection in the battery room, i.e. a cable connection becoming hot enough to initiate a fire.
Electric circuit fire assumptions:
It is assumed that the fire starts at a connector, e.g. at busbar, terminal or similar. Without knowing the actual design of the systems, it is difficult to pinpoint the exact points of failure. Nevertheless it seems unlikely that a single fail would cause a fire to develop, as electrical components have undergone glow wire test and cables are subjected test to evaluate flame spread and smoke characteristics
Battery fire assumptions:
Even though it seems unlikely, it is assumed that a battery module or cell experiences a thermal runaway reaction, causing a fire. To have this happen a series of latent failures would have to manifest themselves. A pathway to such is available in FGC FTA.
Class society rules, DNV-GL in this case, state that fire detection arrangement in a battery room should follow the typical methods applied elsewhere on the ship. The battery management system (BMS) should be the initial method for detecting fire (preferably the stages before thermal runaway).

On the Ærø E-Ferry project Leclanché supplied the battery system. Their battery system is type approved by the DNV-GL (Type approval no. TAE00001WZ) and has several safety features. The features stated in that specific type approval are:

- Throughout the battery modules, linear heat detection is mounted. These are activated at 68°C. Exceeding such temperatures would enable automatic extinguishing, either foam or fog system
- Ventilation ducts, connected to the battery enclosures, have smoke detectors at the "extremity of the duct channel". Detection of smoke would enable automatic extinguishing, either foam or fog system .
- Cooling of the battery cells is managed through liquid cooling.

On project group meeting Friday 11th February, it was stated that the naval architect would select either an ABB, Siemens or CORVUS battery systems. CORVUS's battery system has been applied on the Scandlines hybrid ferries, while the ABB system drives the all-electric Scandlines ferry between Helsingør and Helsingborg. The CORVUS system comes in both a water and air-cooled version. The system is type approved by Lloyds, DNV and ABS, which states the following safety features:

- Integrated thermal runaway gas exhaust system. Vented to external atmosphere rather than the battery room
- Cell-level thermal runaway isolation. TR does not propagate to neighboring cells.
- 4th generation BMS, monitors every cell 2 times per second.
- Independent overtemperature protection according to DNV GL Pt.6 Ch.2 Sec.1 [4.1.5.2] is arranged as hardwired signal tripping high voltage interlock loop. (disconnection at high temperature)

#2 – Fire is detected

Assuming the initiating event is overheating of battery module, which will cause thermal runaway

<u>Main detection systems:</u>

- BMS/BMU is the main detection system for thermal runaway and other abnormalities
  - BMS includes temperature and voltage monitoring
- Smoke sensor (either standard point detector or aspiration with air analysis)

<u>Additional detection system:</u>

- CCTV with fire detection capabilities (smoke pattern or else) with permanent lighting of the room with LED

<u>Reasons for the BMS/BMU to fail</u>

- Faulty programming -> Proper testing and commissioning
- See FGC-FTA -> most faults are immitigable

<u>Reasons for standard point detector to fail:</u>

- Ventilation extracts smoke out of the detector's way -> ventilation design/detector placement
- Clogged by dust, banana flies -> air is filtered, clean operation (electric), 5-year check up
- Vibrations -> very limited due to quiet operation (electric)
- In general, smoke detector is not mentioned as having failed in marine fires

<u>Reasons for CCTV to fail:</u>

- Loss of light -> send a feedback and be visible on screen, action can be taken before fire

Assuming the initiating event is overheating of a terminal/connector

Overheating of a connector or terminal would cause the plastic-based insulation around the connection point to melt, smoke and start burning eventually.

<u>Main detection systems:</u>

- Smoke sensor (either standard point detector or aspiration with air analysis)

Additional detection system:

- CCTV with fire detection capabilities (smoke pattern or else) with permanent lighting of the room with LED
- Inspections with thermal imaging camera, during maintenance or commissioning

#3 – The Master is presented with the alarm
This point is relevant for all rooms and is detailed in Section 2.3.

#4- Confirmation of detection
The discussion relates to **#2** and to the general discussion on automatic detection confirmation.

#5 – Passengers are informed of a "problem" and instructed to proceed to the muster station
This point is relevant for all rooms and is detailed in Section 2.3.

#6 – Distress message is sent to shore
This point is relevant for all rooms and is detailed in Section 2.3.

#7 – Return to port initiated
This point is relevant for all rooms and is detailed in Section 2.3.

#8 – Firefighting initiated
The discussion is still open.

#9 – Continuous communication with passengers and shore support
This point is relevant for all rooms and is detailed in Section 2.3.

#10 – Dock ship at ferry terminal
This point is relevant for all rooms and is detailed in Section 2.3.

#11 – Evacuate passengers
This point is relevant for all rooms and is detailed in Section 2.3.