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Assessment of the Risks Posed by Thermal Runaway within Marine Li-ion Battery Energy Storage Systems - Considering Past Incidents, Current Guidelines and Future Mitigation Measures

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Abstract

Li-ion batteries up to the MW h capacity are increasingly adopted in marine applications, wherein the fire, explosion and toxicity hazards of thermal runaway (TR) events present a unique and complex problem relative to other applications. As such, to perform a critical risk assessment of these hazards this work analyses past incidents. Short circuits related to water ingress and coolant leakage have been the most prominent cause of TR while the majority of TR incidents led to fire or explosion. HAZID analysis was carried out on the battery system, the battery space and the electronic system. Risks were significantly reduced by considering transferable technologies (from automotive and stationary storage sectors) and future technologies. Bow-tie analysis was used to assess the barriers along the threat-consequence pathways of an electrical abuse event leading to the TR hazard and a TR event leading to the battery space failure hazard. The analysis showed that the consequences of battery TR significantly increase if it leads to battery space failure as complete loss of capability, dangers to passengers, and complete ship loss can occur. Further quantitative assessment of proposed improvements is required to determine their effectiveness in hazard reduction for ongoing safety developments.

Keywords: Lithium-ion battery, Maritime, Risk analysis, Hazard identification, HAZID

Abbreviations

HF	Hydrogen fluoride
$ATEX$	Atmosphere Explosible
$BESS$	Battery energy storage system
BMS	Battery management system
DNV	(DNV-GL) Det Norske Veritas – Germanischer Lloyd

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$EMSA$	European Maritime Safety Agency
EV	Electric vehicle
$HAZID$	Hazard identification (method)
IMO	International Maritime Organization
ISC	Internal short circuit
LCO	Lithium cobalt oxide
LEL	Lower explosive limit
LFP	Lithium iron phosphate
LIB	Lithium ion (Li-ion) battery
LTO	Lithium titanate
NCA	Lithium nickel cobalt aluminum oxide
NMC	Lithium nickel manganese cobalt oxide
PMS	Power management system
PPE	Personal protective equipment
PVC	Polyvinyl Chloride
SOC	State of charge
SOP	Standard operating procedure
TMS	Thermal management system
TR	Thermal runaway
TRP	Thermal runaway propagation
VOC	Volatile organic compound

Contents

1. Introduction

The aim to meet Net-Zero emissions by the year 2050, to ensure global warming does not rise by more than 1.5°C as outlined by the Paris Agreement, is driving the uptake in the electrification of transport because such systems have increased operational efficiency and allow the utilisation of renewable energy [1]. There is a particular focus on using Li-ion battery (LIB) technologies in many applications, including automotive and stationary energy storage sectors, as it has high energy and power density, high cycling stability, high working voltage and a lack of memory effect. As such, Li-ion battery energy storage systems (BESSs) provide a great potential to improve ship responsiveness and operational performance [2, 3] whilst reducing emissions. Note, the term "BESS" is used to describe any battery energy storage system that may employ Lead-acid, nickel-cadmium, Lithium-ion or other chemistries, while Li-ion BESSs employ Lithium-ion cells specifically. Further, BESS refers to the energy storage components and auxiliary systems (see Section 2) while LIB specifically refers to the Li-ion energy storage components.

In fact, the growth in the number of marine vessels utilising a Li-ion BESS has been significant since 2010, reaching over 800 vessels in 2023 [4]. However, with nearly 60,000 merchant ships globally on record in 2022, and innumerable smaller vessels such as yachts and fishing boats, it is reasonable to expect significant growth in the number of vessels powered by BESS [5]. Typical installed capacity ranges from hundreds of kilowatt hours to megawatt hours depending on vessel type, from small tugs and yachts to larger heavy transport vessels [4]. Currently, LIBs are predominantly used in applications where distances are short (less than 160 km) [3, 6], while it is anticipated that journeys over 500 km to 1,000 km will require a hybridised system (combined cycle gas turbines or fuel cells) due to the scale of energy required [7, 8]. Positing that industry confidence in LIBs will grow in the foreseeable future, it should be assumed that installations on the scale of MWh will become commonplace

Despite this widespread adoption of LIBs, due to their superior performance characteristics, they have the potential to undergo the rare but very dangerous process of thermal runaway (TR), which leads to complex fires and explosion hazards. An LIB remains in a safe state as long as voltage, current, and temperature are adequately constrained with operational limits. A battery management system (BMS) [9] handles the former two, while a thermal management system (TMS) [10] is responsible for dissipating thermal energy generated by irreversible reactions, including Ohmic heating. However, on rare occasions, excess heat or high temperatures due to abuse leads to the exothermic chemical decomposition of the cell's materials through a complex set of reactions [11–13]. This leads to a positive feedback loop, see Fig. 1, that results in significant heat generation and temperature rise producing flammable and toxic gases, smoke, hot sparks, jet flames and explosions [11, 14]. With the failure of one cell, heat, flames, and short circuits can lead to neighbouring cells also going into TR in a process known as TR propagation (TRP), leading to module TR and module-to-module TRP and ultimately complete pack and system failure [15]. With each level of failure, cell/module/pack, more gas is generated and the more difficult it becomes to prevent further propagation or suppress the fire, hence the aim is to limit failure to the lowest level.

There have been relatively few TR events in LIB-powered vessels (discussed further in Section 3), however, battery integration into marine applications is more complicated while the consequences of TR are more severe compared to other applications, and as such is an ongoing safety concern of the marine sector [17, 18]. Regarding integration, the problem of TR is further accentuated by the unique operational (e.g. large capacity, load fluctuation, location in ship) and environmental conditions (e.g. salt from seawater spray, moisture/humidity, difference in air temperature between battery space and ocean environment, large daily temperature fluctuations) the batteries experience [3, 19, 20]. Considering the consequence of TR, due to the harsh demands of the sea and the confinement of the BESS to a vessel along side the public, crew and other assets, controlling the environment and integrity of the BESS space is

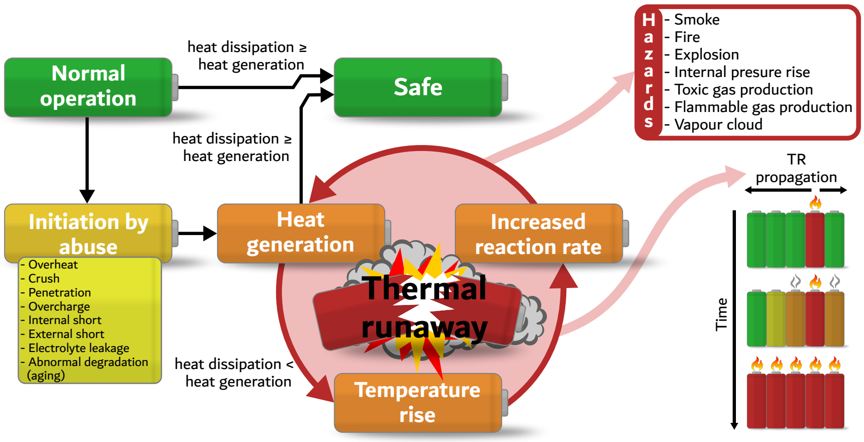


Figure 1: Thermal runaway process – initiation (mechanical, electrical or thermal abuse, or abnormal degradation due to ageing), propagation and resulting hazards (edited from [16]).

a greater concern than in grid systems of a similar scale [21, 22]. Within ships, if the BESS fails there is a need to prevent the fire spreading to the rest of the vessel while directing vented flammable/toxic vent gas away from people. Grid systems on the other hand are generally at a large distance from people and have explosion panels directly to the environment so that deflagration does not contribute to any further fire propagation or risk to persons [23]. Previous incidents have lead to guidance updates [24] but there is a need for further analysis of the risks of Li-ion BESSs in marine applications to be proactive, rather than reactive, in the pursuit of safety.

This work aims to provide an extensive understanding of TR's unique hazard in marine applications. Building on the fundamental theory of battery design and TR behaviour, this work analyses marine battery incidents (Section 3) and regulations (Section 4) to determine the most concerning safety aspects on which an in-depth risk assessment specifically for Li-ion BESS in marine applications will be carried out. For the first time, transferable and future technologies are considered as measures to mitigate risks. A number of methods have been developed or are being developed to reduce the risk of thermal runaway in LIBs. These can be simple, such as periodic checks to assess the state of health of the batteries identifying signs of gassing or reduced available capacity and rack frames to allow for easy removal and quick swapping of LIB modules each with module-level BMSs. They can also be more sophisticated technologies, through all levels of the BESS, including developments in BMS, integration of machine learning, digital twins or intelligent operation & maintenance, cell arrangements, cell chemistries, thermal management technologies, gas sensors, temperature sensors, and fire detection and suppression. Within this, the focus is on transferable and near-to-market technologies.The advantage of individual technologies for specific risk reduction of hazards is discussed in the risk assessment (Section 5) while additional information on the technologies is supplied in the supplementary material.

With this risk assessment, technological and process advances are discussed, while preventative and mitigation barriers are assessed, to define key areas of improvement for greater marine BESS safety. Note, while the transportation of LIBs and products containing LIBs by ship is also a safety concern [25], that is not the focus of this work.

There are many forms of risk assessment techniques, including Event Tree Analysis (ETA), Fault Tree Analysis (FTA), Failure Mode Effect Analysis (FMEA), Hazards Identification (HAZID) and Hazards and Operability (HAZOP) [26]. When failure frequency data is not available semi-quantitative HAZID and qualitative FEMA are useful. HAZID uses broad classes to define frequency and severity that do not require exact quantitative data thus allowing the relative rank and significance of each risk to be determined [27]. For these reasons, considering failure frequency data for marine BESS is generally not available [28], HAZID and FEMA have been used previously to assess marine BESS [28–30].

Key findings from these previous risk assessments include:

(1) That there is little detail on the cause and consequence of failure within the assessment. However, the examined ship is as safe as a normal ferry and that the battery management system (BMS) did not raise concerns over higher accident frequencies [29].

(2) Propagation and fire significantly increase hazards, as such, fire spread has to be minimized between modules and ventilation has to be capable of handling no less than the off-gas of one module. A redundant BMS is important to ensure prolonged monitoring and an emergency battery (module) disconnect function is required to minimise multiple module failures under electrical abuse. The mitigation of explosion and toxicity is a minimum requirement, conditional on all other barriers working as intended. It is also noted that there is a knowledge gap considering battery cell quality assurance for safety and on developing TR testing procedures and acceptance criteria [30].

(3) That systematic reliability-centred maintenance helps to reduce risk across the range of hazards including those related to batteries [31]. Other than the cell level, analysis should account for design safeguards on a cell and system level, the prevalence of manufacture defects (if known) and the procedures and safeguards to prevent abuse (prior to installation, during operation and decommissioning) [28]. Further, the analysis of the impacts of TR should consider cascading failure, fire and toxicity hazards.

General analyses of BESS risks have highlighted that safety can be improved by sharing information on different BESSs and their mitigation methods between ship operators and manufacturers, so that knowledge can be gained about different system setups before accidents occur [32]. Further, the crew's knowledge of the BESS and LIB fire behaviour influences their capability to handle LIB fire incidents. Electrical abuse, collision and cooling methods have been highlighted as the main risks to marine BESS [33]. There is an emphasis put on BMS faults or cell faults leading to over-dis/charge but not other electrical abuse. Studying the collision of ships is complex and it is necessary to consider the construction of the battery room (e.g. spacing and stiffness), location of the battery room (e.g. above/below the water line, stern/bow/midship) and nature of collision (speed and angle).

In this work a comprehensive risk assessment of Li-ion BESSs for marine applications is undertaken to determine methods to improve safety in the sector. First, an overview of marine battery systems is presented (Section 2) to outline the unique challenges of batteries in this application. With this, we will build on the existing risk analyses available by taking findings from previous marine BESS incidents (Section 3) and current marine regulations (Section 4). We will carry out HAZID and bow-tie analyses (Section 5) due to the advantage of HAZID when frequency data is limited and to use bow-tie analyses to address the lack of investigation on the pathway between cause and consequence of marine BESS failure. The HAZID analysis will consider the hazards for the three main system nodes; the battery system, the battery space and the electronic system. Further, it will consider the elemental components of the system nodes and their corresponding hazards, clearly noting the effects on their respective system node as well as the overall battery system and vessel. From the incident analysis (Section 3) two key top events (electrical abuse and battery space failure) are identified and selected for bow-tie assessment. Using this, the objective is to analyse the hazards under current guidelines to determine the areas of most importance and propose improved risk reduction measures.

2. Overview of Marine BESS Construction

In marine applications, a BESS can be used for auxilliary power systems, backup power systems, hybrid-propulsion or full battery propulsion. Where a BESS is used for propulsion (or has a battery installation in a single location greater than 20 kW h [21]), the battery pack/system is housed in a dedicated battery space (a.k.a. battery room) [34], see Fig. 2. The battery room also houses other relevant systems to maintain optimal operational conditions. These subsystems include gas detection and ventilation to remove hazardous gases; fire protection to detect and suppress fires; and environmental systems for temperature and moisture control.

The battery system consists of one or more battery packs with pack-level BMS to control sub-packs and conduct high-level sensing, including detecting and shutting off critically failed sub-packs. The sub-pack is the smallest unit that can be electrically isolated, having its own sub-BMS with the functions of a typical BMS. The sub-pack is made up of one or more modules, that are typically housed into racks.

The performance and safety of the battery are maintained through communications between the BMS and thermal management system, and the BMS and wider ship power systems such as the power management system, charger, consumers and integrated automation system (IAS), see Fig. 2. The thermal management of the battery can either be

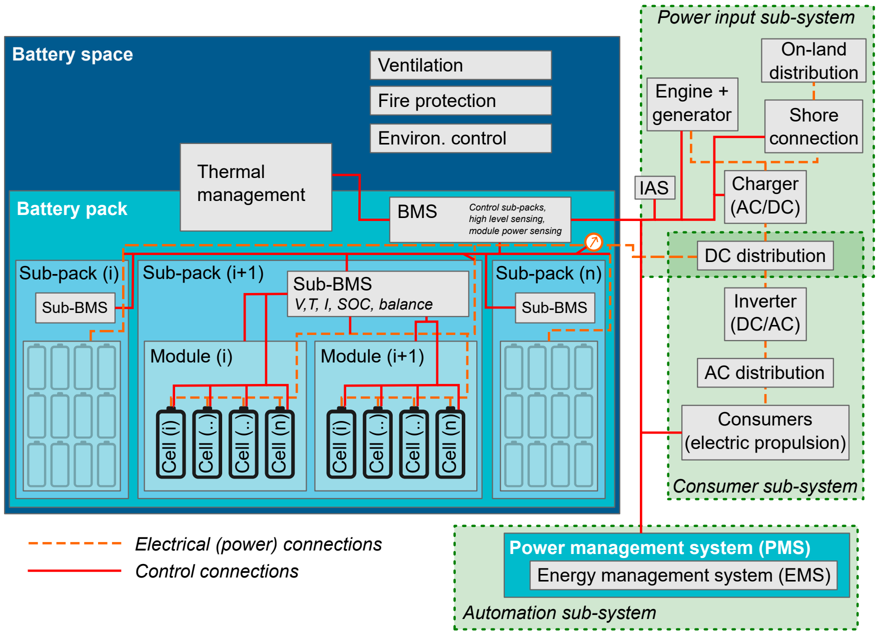


Figure 2: Block diagram of the generic power system on a marine vessel with BESS (edited from [34]).

air-cooled or liquid-cooled by the use of cooling pipes throughout the battery modules. Air-cooling is more simple than liquid-cooling, but liquid-cooling provides higher heat dissipation capabilities [35].

For contexts, much of the BESS is the same as that for grid applications. The battery space on a ship is somewhat comparable to the ISO container unit used in grid storage systems. Ships, depending on their category, have capacities ranging from 100 kW h to 40 MW h [4, 36], typically distributed across multiple battery rooms to optimise performance and safety. In contrast, grid-scale BESS consists of ISO container units with capacities of 3 MW h to 5 MW h each, which are combined to achieve total system capacities at the GWh scale. Within the room/container, the BMS, rack mounting of cells and thermal management will utilise similar technologies. The power distribution systems are also similar, with both having AC/DC inverters to the grid for charging, but the stationary battery also discharges to the grid while the ship battery distributes energy by DC and AC circuits [37–39].

Further detail on the operation and safety of the battery system/space, including the ventilation and fire suppression sub-systems, is discussed in Section 3.8 and Section 4 after a review of marine BESS incidents.

3. A History of Maritime Incidents Related to Battery Energy Storage System Failures

Since 2012 there have been at least 12 incidents of battery failures on vessels fitted with BESSs, as shown in Table 1. These incidents have been across various vessel types, battery sizes and new/retrofit systems. Where information is available, the causes and consequences of these incidents are detailed in the following Sections 3.1 to 3.7. Note, the frequency of BESS failure (the number of BESS incidents in a year, Table 1, as a fraction of operational

Table 1: Record of battery energy storage system incidents on marine vessels ("not applicable (na)" in relation to the year converted implies the ship was a new build electric(-hybrid) vessel).

Year of incident	**Year built/converted**	**Vessel**	**Type**	**Battery Size (kWh)**	**Root cause**	**TR Cause**	**Consequence**	Ref.
2012	2005/2011	Campbell Foss	Tug	65	Software error	Overcharge	Fire	[24, 40–42]
2015	1997/2013	Prinsesse Benedikte	Ro/RAX ferry	2700	Flooding	Short circuit	Explosion	[24, 30]
2015	Unknown	Testlab Borås	Unknown	Unknown	Overcharging	Propagation testing	Explosion	[24]
2018	1999/2016	Vardehorn	RO/RO cargo	Unknown	Coolant leakage	Short circuit	Smoke development	[24, 43]
2018	2018/na	Møkstrafjord/Lagatun	Passenger, RO/RO cargo	1200	Coolant leakage	Short circuit	Smoke development	[24, 44]
2019	2006/2019	Ytterøyningen	Car ferry	1989	Coolant leakage & slat water	Short circuit	Fire & Explosion	[24, 45–47]
2019	2003/2014	Losharik	Submarine	Unknown	Unkown	Short circuit (assumed)	Fire & explosion	[48]
2020	2019/na	Seacosco Congo	Offshore support	452	Condensation	Short circuit	Fire	[24, 49]
2020	2019/na	Brim	Tourist cruise	790	Salt water (assumed)	Short circuit	Fire	[24, 50]
2022	2019/na	Bjørøyvær	Work/service boat	180	Unknown	Unknown	Smoke development	[24, 51]
2022	2021/na	Viking Gymir	River cruise	745.5	Unknown	Unknown	Fire & explosion	[24]
2023	2019/na	Ellen	Ferry	4300	Unknown	Unknown	Fire	[52]

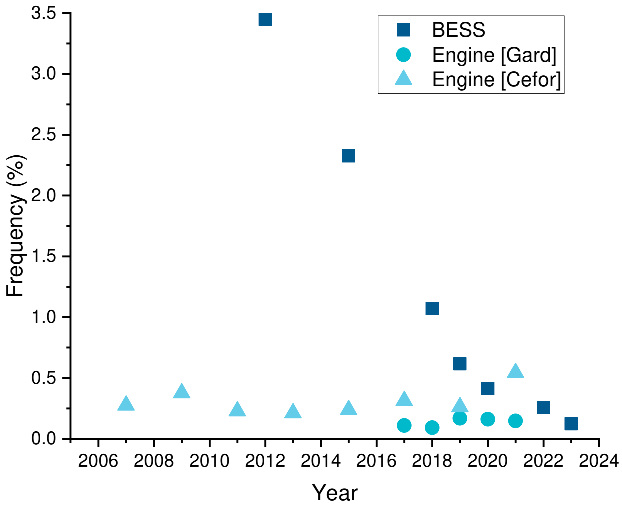


Figure 3: Frequency of fire incidents related to BESS and traditional engine power in marine vessels (engine data from Gard [53] and Cefor [54]).

marine vessels with BESS [4] in the same year) was large in the early years, however in recent years the frequency of failure is on par with the frequency of engine fires, see Fig. 3. Following the details in Sections 3.1 to 3.7, a summary is presented including key learning outcomes in Section 3.8.

3.1. Campbell Foss

The tug boat Campbell Foss experienced a fire within the battery compartment situated in the engine room. Due to the heat, the PVC venting duct melted so gases spread to the engine and ignited [40, 41]. The boat was towed to shore and the engine room FM-200 fire suppression was engaged and successfully extinguished the fire. Using thermal imaging it was determined the fire was not spreading and firefighters went into extinguish the smouldering remains. The boat engineer suffered smoke inhalation injuries. The cause of the fire was a failure of one of the cells in the 10-cell series. A software error of the BMS led to the overcharge protection circuitry not being operated, as such several overcharging events of the cell over two months led to its failure. Further, the alarm and monitoring system did not showcase this information which caused a delay in hazard response.

Risk assessment of repairs led to the battery being moved from the engine room to the stern void space (which

Figure 4: Thermal imaging of firefighters in high-temperature chemical resistant suits tackling fire aboard MF Ytterøyningen (Image courtesy of Bergen Brannvesen/City of Bergen Fire Department).

allowed a simplified ventilation system design over other areas). Further, upgrades were made to new bulkheads and structures for new battery compartment; the addition of rupture disks from the battery compartment into the void (between it and the hull) to allow for gas expansion; air conditioning; FM200 suppression; and containment boxes to direct escaping gases/fire [55].

3.2. MF Ytterøyningen

A fire was detected in the battery room of the Ytterøyningen ferry and they immediately returned to shore to evacuate the passengers before actively fighting the fire [24]. Almost 2 hours after the initiation of the fire, Novec 1230 (gas/aerosol) and the saltwater sprinkler extinguishing systems were activated consecutively. The firefighters (see Fig. 4) initially took defensive action spraying foam into the battery room, where shortly after they reported the incident under control. However, 30 minutes later, new smoke appear which the firefighters found to be impenetrable to the IR camera, electing to retreat.

Following a later reduction in smoke density a firefighter entered the room where he commented on feeling pain. Analysis, at a later time, attributed this to HF attacking his suit, where after the event 10ppm was measured due to NOVAC. Following this, temperature measurements were cautiously made by going aboard every 30 minutes, which showed that the temperature stabilised overnight. However, at 1 am temperature rise was observed, prompting an increase of the sampling rate to once every 15 minutes. On taking the measurements it was commented that steam was rising from the hatch, and so at 5 am the hatch was left open as the danger was assumed low. At 7 am there was a large explosion that damaged vehicles near the ship, no personnel were close at the time. The whole incident lasted 24 hours.

From incident analysis, it is reported that a short circuit was the cause of the TR event. A gasket of module, damaged during maintenance, led to coolant leaking from the module. This then caused short-circuiting of the external voltage terminals leading to heating that caused the insulation of the wire to catch fire, and ultimately, the occurrence of TR in the module. Additionally, some safety functions were disconnected during maintenance, disabling the protection otherwise provided by the BMS and fuses, thereby preventing the activation of the alarms.

Once the fire had been detected the release of NOVAC also exacerbated problems by causing more flammable gas accumulation as NOVAC operation requires a sealed room. Further, the salt water spray led to arcing and more fires as there was no hood above the battery stacks. This was determined by the coincidence of the salt water spray and the increase in temperature. The damage of other modules did not coincide with the initial module, and the random pattern is attributed to the water spray causing sporadic shorts.

Further analysis showed that the neighbouring room was damaged and the door to the battery room was blown inwards. This is attributed to a gas explosion outside the battery room. The likely reason for this is the fire deformed the modules that prevented their burst disks from working, causing an initial accumulation of gas in the battery room. Then, when the NOVAC operation sealed off the battery room the gas could only escape through the keel by an opening for the bulge pumps. On opening the hatch, air entering the area/neighbouring room led to an explosive ratio, ignited and blew the battery room door in and sent a shock wave away from the boat.

Following the accident, the Norwegian Maritime Authority recommended all battery-operated vessels to carry out a new risk assessment of the hazards from the possible accumulation of explosive gases [56]. Further, the battery manufacturer, Corvus Energy, released a warning to other vessels to ensure communication is maintained between the power management system and the BMS for important fault detection, and in the event of TR to not shutdown the battery system and contact Corvus Energy immediately [57]

3.3. Losharik

The Losharik is a Russian nuclear submarine initially built in 2003 and installed with silver-zinc batteries. At a later date, the batteries were replaced with Li-ion chemistry [48]. A fire was detected in the battery compartment and fought using a Freon-based liquid oxygen system, standard for fighting fires on this type of vessel. Tackling the blaze was unsuccessful and the fire led to an explosion and the loss of life of 14 crew members. The root cause of the fire is not publicly known but is assumed to be related to a short circuit, possibly due to operating conditions that led to high currents and in turn temperatures that melted the insulation of the wire.

3.4. MS Brim

The MS Brim is a catamaran ferry/sightseeing boat that caught fire in Oslofjord [58]. The fire was first detected in the engine room adjacent to the battery room because the engine room was fitted with CCTV while the battery room was not, and ground fault alarms raised relating to the BESS were ignored as one of many that kept occurring since the vessel was put into service. With the smoke in the engine room, it was assumed that an engine fault/fire was the

Figure 5: The remanence of battery room on MS Brim (Image courtesy of Kripos).

cause and NOVEC was released. After this, the fault was determined to be from the battery room so NOVEC was released there as well, 12 min after ground fault detection. The boat was then towed to shore where it took 7 days to fight the fire with suction to remove explosive gases from the battery room while replacing air with nitrogen. One crew member was hospitalized due to inhalation of gas/smoke emitted to the deck.

The probable cause for the event is attributed to a short circuit due to the ingress of salt water through the ventilation outlet, or due to condensation and salt build-up over time. The salt water first led to a short in the upper module (60V DC) of battery stack 6, indicating a ground fault. After, the bottom two modules shorted (120V DC) showing signs of arcing, propagation then followed through to stacks 5 and 4.

The resulting fire completely destroyed the battery space (see Fig. 5), while there was serious smoke and corrosion damage to adjacent rooms.The heat was so intense that it caused damage to the bulkheads but the fire was contained to the battery room. As a result, it was recommended that IP ratings should be increased to at least IP44, the battery room should be protected from seawater ingress (i.e. consider any opening, inlet/outlet vents, operating conditions), and have continuous ventilation.

3.5. Bjørøyvær

The Bjørøyvær was alerted to an incident in the battery room by the fire alarm [24]. Firefighters acted to remove a module that was smoking and overheating along with adjacent modules. No extensive damage was caused but firefighters put themselves at significant risk. The cause of the module failure is under investigation.

3.6. Viking Gymir

The Viking Gymir experienced an explosion in the battery space leading to the evacuation of passengers with some smoke inhalation injuries but no loss of life, while the cause is not publicly known [24, 59].

3.7. *Ellen*

The Ellen ferry battery compartment caught fire, cause unknown, but was extinguished by foam automatic fire-fighting system [52, 60].

3.8. *Summary and Learning Outcomes*

Table 1 shows that the most prominent TR cause is short circuit by water, where the root cause of 50% of these incidents is related to coolant leakage. This highlights that the use of non-conductive liquid coolants, such as dielectric fluids (used for cooling automotive LIBs [61]), within cooling pipes would add an additional layer of protection. In the other short circuit incidents seawater and condensation build-up have been significant contributing factors. As such, the ingress protection rating of components has been increased to IP44 [58] while ventilation outlets have to be positioned and designed to prevent seawater ingress. While a higher IP rating offers additional benefits, a battery on a hybrid or all-electric vessel is not expected to be submerged during normal operation; therefore, a greater IP rating such as IP67 (temporary submersion in water up to 1 meter for up to 30 minutes) is not strictly necessary. Notably, 75% of incidents led to fire or explosion, indicating that barriers to stop escalation to TR propagation were not effective and need updating so that most failures lead to smoke development only. Additionally, from the description of the incidents, it is clear there is a lack of detailed information for many events. This highlights the need for clear and open reporting for all stakeholders to learn from through knowledge sharing.

The incidents above highlight four key areas where lessons were learnt:

1. fault detection;
2. fire suppression and fighting;
3. gas generation; and
4. LIB safety knowledge.

Table 2 provides a summary of these key findings, and those summarised by DNV [24], relating to cause prevention, TR propagation prevention and gas dispersion prevention. Further discussion of the four key learning areas is presented next.

Fault detection can be improved by maintaining BMS connections at all times (ensuring they are not disconnected during maintenance as in the Campbell Foss incident); using CCTV to visually monitor the battery from afar reducing risks to personnel and providing additional data on top of BMS readings; and improving ground fault detection circuitry to reduce the number of false positives so that personnel are less likely to disregard an alarm. It has also been suggested that each rack/module should have an individual BMS [24].

Table 2: Thermal runaway, fire, explosion and thermal propagation prevention methods.

Cause Prevention	TR Propagation Prevention	Gas Dispersion Prevention
- Improvement on the watertight nature of the battery room and doors. - Stricter requirements on ventilation ducts and environmental protection of the room. - Minimum of IP44 rating for ingress protection. - Leakage detection systems.	- The fire-extinguishing capacity of fresh-water-based systems increased from 30min to 60min. - No requirement for sea-water extinguishing system. - Option for combined gas and water spray system for 30mins. - No requirement for gas system cooling.	- Room and ducts should be gas-tight. - In/outlets of gas ventilation/extraction direct to open air. - No direct access to battery room from public space. - 3 m toxic zones around outlets.

The use of water in fire suppression has been shown to be effective but can lead to further damage to the system and arcing. Therefore, hoods have been suggested (MF Ytterøyningen) to prevent ingress, however, this may affect the penetration and cooling potential of the water cooling. It has also been suggested to use direct injection into an affected area/module, but this would require personnel to enter the room, or not starting water suppression unless propagation starts [32]. To mitigate water-related hazards drainage from the rack and individual rack-level water nozzles (for fire suppression) have been suggested [24]. Gas suppression (NOVEC, FM200) can lead to additional HF contamination and the build-up of flammable gases due to sealing off the ventilation system, while its effectiveness as a fire suppressant in battery rooms is uncertain. As such, there is clearly room to develop more effective fire suppression methods.

The build-up of flammable gases and the related fire/explosion hazard can be minimised by: 1) ensuring structural integrity of ducting, i.e. not using plastic ducting that melts; 2) maintaining active ventilation during battery failure, which goes against the use of gas fire suppression systems; 3) ensure battery room is gas tight besides the ventilation system, i.e. gas can not escape through other piping like the bulge pumps; 4) the battery is not in the engine room, so there are minimal sources of ignition; and 5) there is controlled direction of gases from cells and modules. Further, controlled explosion paths from the battery room should be a consideration.

Knowledge is a key aspect of safety and effective incident management. Therefore, personnel should be made aware of the specific hazards and behaviours of battery fires knowing when best to shut down the system, while specific battery fire-trained firefighters should respond to the incident. Further, firefighters should be aware of the HF potential and have appropriate protective suits.

The latest set of guidance from the DNV incorporates these learning outcomes and also states that the battery room capacity should be limited to 5 MW h (hence larger BESS should be split across multiple battery rooms) [21]. Further specifications are given for the watertight static pressure limit; the classification of 'extended hazardous area zone 2' around ventilation inlets and outlets due to explosion risk; and that only water pipes related to the BESS are allowed in the battery room. Additionally, ventilation in/outlets should be A0 fire-rated, not allowing the propagation of flames through the ducts but allow temperatures above 180°C, while walls between rooms should be A60 rated (temperatures must not exceed 180°C for 60 minutes).

This guidance [21] also includes the requirement to pass a TR propagations criteria in which 1) there should be no propagation between cells within a module or 2) there is no propagation between modules as long as the total capacity of cells within the module that go into TR is less than 11 kW h (with or without extinguishing agent activated). The thermal runaway trigger should be by overcharging or overheating, the initiation cell should be in the worst-case location and orientation for propagation and the observation period is 24 hours. The system must successfully pass the chosen test criteria (option 1 or 2) 3 times under a minimum ambient temperature of 45°C, with all the cells being electrically connected, unless the testing is by overcharging then this cell can be isolated. Success in criteria 1 is defined as the failure of the abused cell only with no external signs of TR in other cells, any propagation to other cells within the module does not meet the functional safety requirements. For batteries designed to allow propagation between cells but not modules, success is achieved with failure only within the abused module. Finally, the integrity of the liquid cooling system should be maintained.

4. Current Regulations and Guidelines

Regulations on shipping are provided by international and national bodies. However, the International Maritime Organization (IMO) has not provided any rules or conventions on the use and safety of Li-ion BESS [62]. Further, the international maritime treaty Safety of Life at Sea (SOLAS), which defines requirements for power and generator sets and the protection against related electrical hazards, does not define any specific rules for Li-ion BESS [2]. Recently the European Maritime Safety Agency (EMSA) has published its " Guidance on the Safety of Battery Energy Storage Systems (BESS) on Board Ships" [63]. This document provides non-mandatory guidance that aims to understand the hazards of BESS and the measures to reduce their risks aboard ships, with details on the BESS design, installation, testing, operation, maintenance, and personal training. Historically, however, key nation-states with important and globally renowned maritime organisations have provided the bases of Li-ion BESS requirements and safety.

The Norwegian Maritime Authority (NMA) is at the forefront of the development and use of Li-ion BESS [64]. This guideline aims to maintain the same safety on BESS ships as conventional ships. It includes the definition of a propagation test, where at 100% SOC there should be no module-to-module propagation even with the BMS and fire extinguishing system disconnected. Also, there is the requirement to analyse the explosion potential and path, as well as the gas composition and quantity. This is only specified for batteries over 20kWh, under this there is only the need to do a risk analysis against working environment regulations.

The Maritime & Coastguard Agency of the United Kingdom provide certification and guidance, including for

BESS, according to The Workboat Code [65] and Marine Guidance Note 550 [66]. This includes rules on the design, installation and testing of the battery, considering (but not limited to) the location of BMS, protection against overheating (even in the event of power loss), safety even if exposed to seawater, room size and location, ventilation, signage and fire safety precautions and procedures.

The American Bureau of Shipping (ABS) documents the (mandatory) requirements for the use of Li-ion BESS in ships, with the purpose of establishing safety guidelines for owners, operators, shipyards, designers, and manufacturers [67]. Requirements focus on batteries greater than 25kWh, with a distinction between batteries used as a main source of power or an emergency source of power. Similar to other organisations, requirements cover design, testing, installation, risk assessment, operation, maintenance and commissioning surveys.

Based on these regulations, classification bodies set out rules that ships must abide by to obtain and retain classification certification to ensure the ship and its components are safe, reliable and environmentally sound. The rules also include the standards for the life-cycle and operation of LIBs in marine vessels, including conception of the battery design and manufacturing (including abuse testing), transportation and installation into the battery space, safety procedures (including the fire extinguishing, ventilation and emergency shutdown mechanisms) and the maintenance of the system. These allow a safer and smoother commercial adoption of marine electric propulsion to meet the environmental targets set by the UN and IMO.

These bodies are generally more comprehensive and up-to-date than the national maritime organisations. Classification bodies are numerous, however, the EMSA recognises only 11 such bodies [68]. These include DNV, which defines rules on the use, design and safety of Li-ion BESS specifically for power (propulsion) applications or where a single BESS space is greater than 20kWh [21], incorporating learnings from earlier guidelines [34, 69, 70]. Note that although it is beyond the scope of this work, DNV also provides similar rules for battery systems under 20 kWh [71], ensuring their proper protection (e.g., gas-tight steel enclosure with ventilation) and placement in low-risk areas, avoiding locations such as open decks, sleeping quarters, or engine rooms. Additionally, the rules are based on standard IEC 62619, 'Secondary Cells and Batteries Containing Alkaline or Other Non-acid Electrolytes' and 'Safety Requirements for Secondary Li Cells and Batteries, for Use in Industrial Applications' [2]; Lloyd's Register of Shipping which provides guidance on battery installations and the number of required BMS alarms and detectors, and recommends a water-based fire extinguisher like DNV-GL [32]; and Bureau Veritas, which has additional standards such as painting the battery room with antistatic paint to prevent the build-up of external charges to the batteries [72]. Further, incorporated in battery design and testing is the standard IEC61508 [34] for BMS guidelines and UL 9540A for propagation testing [73].

Whilst these regulations address safe BESS operation for maritime use there are some inadequacies concerning

TR detection and prevention. The IMO does not provide a dedicated specification while the ESMA's guidelines are non-mandatory, resulting in a lack of unity between the existing standards. Section 3 shows that several TR events were influenced by the presence of seawater and condensation within the battery room. Given the unique conditions of marine BESS – being surrounded by open water – the current regulations do not address the need for more advanced ventilation and filtration in and out of the battery room. Despite EMSA's recommendation to increase the IP ratings of battery rooms to IP44, this is not enforced and only applies to European-operated vessels.

The existing mandatory regulations have limited coverage of thermal runaway procedures and prevention methods. The ABS and NMA do not address thermal runaway prevention, whilst the Maritime & Coastguard Agency does address fire safety precautions and procedures. However, these regulations do not address the difficulties of marine scenarios, such as non-cyclical, repeated loading due to rough waters leading to mechanical stress cycles, and increased levels of humidity and water exposure.

There also exists a lack of training for personnel on dealing with thermal runaway, as noted with Bjørøyvær, where the firefighters removed a module that was overheating [24]. Despite the fast action preventing damage, the firefighters exposed themselves to risk, as they had not been trained on how to properly deal with a battery module that was a potential thermal runaway hazard. Therefore, guidelines should include the training of personnel on BESS marine vessels for the safe handling of BESS safety events.

4.1. Summary

The current guidance provides a sufficient basis for safety, however, a lack of consistency between classification societies leads to different solutions in terms of safety [32]. Further, it is noted that regulations are not complete while the introduction of international maritime regulations is a lengthy process, as such BESS safety has to be developed independently and shared openly.

5. Risk Assessment

General knowledge of battery systems and the advantages of transferable and near-future technologies (detailed in the supplementary material), findings from maritime BESS incident (Section 3) and an understanding of current regulations (Section 4) are used to assess the risks of marine BESS systems and identify methods for reducing these risks. Two risk assessment methods are applied, first, HAZID (Section 5.1) considers the broad hazards related to the BESS safety for three system nodes (1) the battery system, (2) the battery space and (3) the electronics system. Second, the bow-tie method (Section 5.2) is applied to analyse the key hazardous events (electrical abuse and battery space failure) in more detail. Further, this work takes a chemistry agnostic approach within the following risk assessments to provide the most practical guidance for marine battery hazard reduction, enabling the design and risk assessment of individual battery systems.

5.1. HAZID

The HAZID analysis is based on the existing hazard analysis by the EMSA/DNV-GL [30] along with the fire safety review [32] and is updated to consider the prevention and mitigation methods outlined by the most recent guidelines [21]. The existing hazards are expanded on while additional hazards are included based on the lessons learnt from Section 3 and the authors' opinion. This is further developed to consider the use of existing technologies from other LIB applications and technologies available in the near future to assess their risk mitigation potential.

The HAZID method uses a flow sheet considering the unit/item that the hazard is related to, a description of the hazard including causes, consequences, preventative and mitigating measures (a.k.a. barriers) and a value for frequency (probability) and consequence (severity) classes [27]. The classes are used when it is difficult to measure or estimate the frequency and consequences accurately but allow a broad indication of hazards' relative probabilities and severities. The frequency and consequence classification categories (1–5) are defined according to Tables S1 and S2 in the supplementary material. These classifications are summed to produce a risk rank where a risk rank ≤ 5 is broadly acceptable; a risk rank of 6–7 is somewhat acceptable but should apply the "as low as reasonably practicable" (ALARP) principle and consider further risk reduction analysis; and a risk rank ≥ 8 requires risk reduction. Once the initial HAZID analysis has been carried out considering existing barriers, the risk rank of each hazard that is determined unacceptable (risk rank ≥ 6) can be further analysed to determine additional barriers to reduce their risk rank leading to an updated or final HAZID table. Below are the results following this method.

5.1.1. HAZID Results and Discussion

The resulting HAZID analysis is presented in Table 3 where each hazard is related to a system node (1 - battery system, 2 - battery space, 3 - electrical and control system), element (1 - cell, 2 - module, 3 - battery system, 4 - enclosure, 5 - ventilation, 6 - climate control, 7 - fire suppression, 8 - PMS/BMS, 9 - convertor, 10 - emergency shutdown) and hazard (sequential numbering, n=1:29), resulting in a reference number of the form *Ref. No. 1.1.1.*

Table 3: Initial HAZID risk assessment of Li-ion BESS for marine applications.

Description of unit			Description of hazard					Risk (Initial)		
Ref. No.	System Node	Element	Hazard	Cause(s)	Consequence(s)	Preventive Measures	Mitigating Measures	Freq. Class	Cons. class	Risk Rank
1.1.1	Battery System	Cell	Thermal runaway	Mechanical abuse: Rack tipping over (incorrectly fixed), Impact/crush from other falling equipment or maintenance, vibration, pressure (subsea)	- High temperature - Gas generation including flammable and toxic species - Fire - Explosion - Propagation leading to module failure - Loss of battery capability	- BMS to monitor temperature, alarm - Mechanical protective structure - Cooling system with redundancy - Define and follow SOP - Oil immersion or potting for vibration resistance	- Automatic isolation of failed cells/strings - Enhanced room ventilation to the external environment for gas removal - Emergency shutdown of battery system - Thermal barriers (insulation) and fire direction control between cells and modules, minimise propagation - Fire suppression system in battery space	2	2	4
1.1.2	Battery System	Cell	Thermal runaway	Electrical abuse: ISC, over/under charge, too high C-rate, external short circuit (seawater/condensation coolant), ageing, BMS failure	- High temperature - Gas generation including flammable and toxic species - Fire - Explosion - Propagation leading to module failure - Loss of battery capability	- BMS to monitor voltage and current, alarm - Housing so debris i.e. loose metal can not cause short - Cooling system with redundancy - Define and follow SOP - e.g. prevent shorts from maintenance - Redundant BMS	- Automatic isolation of failed cells/strings - Enhanced room ventilation to the external environment for gas removal - Emergency shutdown of battery system - Thermal barriers (insulation) and fire direction control between cells and modules, minimise propagation - Fire suppression system in battery space	3	2	5
1.1.3	Battery System	Cell	Thermal runaway	Thermal abuse: External heating, cooling system failure, Low temperature	- High temperature - Gas generation including flammable and toxic species - Fire - Explosion - Propagation leading to module failure - Loss of battery capability - (low temperature) Accelerated ageing, dendrite growth	- BMS to monitor temperature, alarm - Cooling system failure alarm - Cooling system redundancy	- Automatic isolation of failed cells/strings - Enhanced room ventilation to the external environment for gas removal - Emergency shutdown of battery system - Thermal barriers (insulation) and fire direction control between cells and modules, minimise propagation - Fire suppression system in battery space	2	2	4

Table 3 (cont.): Initial HAZID risk assessment of Li-ion BESS for marine applications.

Description of unit			Description of hazard					Risk (Initial)		
Ref. No.	**System Node**	**Element**	**Hazard**	**Cause(s)**	**Consequence(s)**	**Preventive Measures**	**Mitigating Measures**	**Freq. Class**	**Cons. class**	**Risk Rank**
1.2.4	Battery System	Module	Thermal runaway	Electrical abuse: external short from wiring issues, water ingress, coolant leakage, cell imbalances	- High temperature - Increased gas generation (compared to cell) including flammable and toxic species - Fire - Explosion - Propagation leading to rack/system failure - (increased) loss of battery capability	- BMS to monitor temperature, voltage and current, alarm - Housing to prevent water ingress or coolant pooling - Cooling system with redundancy - Define and follow SOP, periodic cell balance check - Redundant BMS	- Automatic isolation of failed module - Enhanced room ventilation to the external environment for gas removal - Emergency shutdown of battery system - Thermal barriers (insulation) and fire direction control between modules and racks, minimise propagation - Fire suppression system in battery space	3	3	6
1.2.5	Battery System	Module	Thermal runaway	Cell TR propagation	- High temperature - Increased gas generation (compared to cell) including flammable and toxic species - Fire - Explosion - Propagation leading to rack/system failure - (increased) loss of battery capability	- Thermal barriers - Gas and fire control, away from other modules to external vents - Cell orientation (vent position) - Circuit elements (CID, PTC, fuse) - Propagation testing	- Automatic isolation of failed module - Enhanced room ventilation to the external environment for gas removal - Emergency shutdown of battery system - Thermal barriers (insulation) and fire direction control between modules and racks, minimise propagation - Fire suppression system in battery space	2	3	5
1.2.6	Battery System	Module	Thermal runaway	Mechanical abuse: Impact/crush from other falling equipment or maintenance, vibration, pressure (subsea)	- High temperature - Increased gas generation (compared to cell) including flammable and toxic species - Fire - Explosion - Propagation leading to rack/system failure - (increased) loss of battery capability	- BMS to monitor temperature, alarm - Mechanical protective structure - Cooling system with redundancy - Define and follow SOP	- Automatic isolation of failed module - Enhanced room ventilation to the external environment for gas removal - Emergency shutdown of battery system - Thermal barriers (insulation) and fire direction control between modules and racks, minimise propagation - Fire suppression system in battery space	2	3	5

Table 3 (cont.): Initial HAZID risk assessment of Li-ion BESS for marine applications.

Description of unit			**Description of hazard**					**Risk (Initial)**		
Ref. No.	**System Node**	**Element**	**Hazard**	**Cause(s)**	**Consequence(s)**	**Preventive Measures**	**Mitigating Measures**	**Freq. Class**	**Cons. class**	**Risk Rank**
1.2.7	Battery System	Module	Thermal runaway	Thermal abuse: External heating, cooling system failure, fire from gas ignition	- High temperature - Increased gas generation (compared to cell) including flammable and toxic species - Fire - Explosion - Propagation leading to rack/system failure - (increased) loss of battery capability	- BMS to monitor temperature, alarm - Cooling system failure alarm - Cooling system redundancy - Thermal barriers - Fire barriers	- Automatic isolation of failed module - Enhanced room ventilation to the external environment for gas removal - Emergency shutdown of battery system - Fire suppression system in battery space	2	3	5
1.3.8	Battery System	System	Fire	Module TR propagation, fire from gas ignition	- High temperature - Severe gas generation (compared to a module) including flammable and toxic species - Total system failure - Total loss of battery capability - Loss of battery space (room) - Loss of vessel	- Thermal barriers - Circuit elements (module/rack electrical isolation) - Propagation testing - Fire controlled to one module (prompt action act on alarms, CCTV)	- Enhanced room ventilation to the external environment for gas removal - Emergency shutdown of battery system - Fire suppression system in battery space - Fireproof insulation (A60/A0) to adjacent rooms	2	5	7
1.3.9	Battery System	System	Gas Generation	Cell, model and system TR failure	- Fire - Explosion - Toxic environment - Total system failure - Total loss of battery capability - Loss of battery space (room)	- Measures associated with cell, module and system failure (see 1.1.x/1.2.x/1.3.8)	- Enhanced room ventilation to the external environment for gas removal - Emergency shutdown of battery system - Fire suppression system in battery space - large room volume with active circulation - Fireproof insulation (A60/A0) to adjacent rooms - Gas sensors, increase ventilation at 25% LEL - Explosion-proof (ATEX) rated extraction fan - Ship evacuation at 25% LEL	3	3	6

Table 3 (cont.): Initial HAZID risk assessment of Li-ion BESS for marine applications.

Description of unit			**Description of hazard**					**Risk (Initial)**		
Ref. No.	**System Node**	**Element**	**Hazard**	**Cause(s)**	**Consequence(s)**	**Preventive Measures**	**Mitigating Measures**	**Freq. Class**	**Cons. class**	**Risk Rank**
1.3.10	Battery System	System	Explosion	Gas generation	- Total system failure - Total loss of battery capability - Loss of battery space (room) - Loss of vessel - Rupture of battery space/damage external to battery room/ship structural integrity compromised - gas escape, explosion external to the battery room (including above deck and off vessel)	- Gas sensors, increase ventilation at 25% LEL - Explosion-proof (ATEX) rated extraction fan - Ensure battery room is sealed/no paths for gas to travel to other areas e.g. pipes for bulge pumps - Dilution with CO2 or N2	- Enhanced room ventilation to the external environment for gas removal - Emergency shutdown of battery system - Fire suppression system in battery space - large room volume with active circulation - Fireproof insulation (A60/A0) to adjacent rooms - Ship evacuation at 25% LEL - explosion rupture disks	2	5	7
1.3.11	Battery System	System	Excess heat (electrical cabling and contacts)	- Improper specification - poor design - Assembly error	Battery thermal abuse (see 1.1.3/1.2.7)	- Design evaluation - Well-defined and followed commissioning and maintenance procedures - Fire-resistant materials - Non-toxic materials	See 1.1.3/1.2.7	2	2	4
1.3.12	Battery System	System	Electrical arcing	Water from fire suppression	- Extremely high temperatures - melting of metal components - Unpredictable propagation pathway - Fire - Flying objects e.g. molten metal (possible impact damage) - Blast pressure	- Shroud/hoods to prevent water ingress - De-energize battery - Ground Fault Circuit Interrupters	- Enhanced room ventilation to the external environment for gas removal - Emergency shutdown of battery system - Fire suppression system in battery space - Fireproof insulation (A60/A0) to adjacent rooms	3	3	6
1.3.13	Battery System	System	HF gas Generation	From fire suppression (Novec)	- Severe toxicity hazard - Hazard to firefighters - Residual hazard after event	- Minimise Novec use	- Avoid entry to room - Appropriate PPE if firefighters (or other personnel) have to go in - Measure quantity of HF and clean up before battery replacement	2	4	6

Table 3 (cont.): Initial HAZID risk assessment of Li-ion BESS for marine applications.

Description of unit			Description of hazard					Risk (Initial)		
Ref. No.	System Node	Element	Hazard	Cause(s)	Consequence(s)	Preventive Measures	Mitigating Measures	Freq. Class	Cons. class	Risk Rank
2.4.14	Battery space	Enclosure	Explosion	Off gas ignition	- Fire (TR) - Sparks - Electrical/hot equipment - Oxygen from external environment - Gas escape - See 1.3.10	- See 1.3.10	- Gas-tight enclosure - Only BESS in room - Negative pressure -ATEX vents - See 1.3.10	2	5	6
2.4.15	Battery space	Enclosure	Structural failure	Collision/grounding	- Deformation of room, displacement of racks, damage to batter, TR - Not water-tight, water ingress, short circuit - Not sealed against gas escape, fire/explosion outside of battery room - Deformation of vent ducting, gas not vented properly, build up, explosion - see 1.1.1/1.2.6	- Situate the room away from areas prone to impact (i.e. aft of collision bulkhead) - Allow flexibility in vent ducting - Proper commissioning and service procedures	- Battery shutdown - Acoustic sensor to infer damage - see 1.1.1/1.2.6	2	4	6
2.4.16	Battery space	Enclosure	Structural failure	Design/installation error	- Racks come loose, impact/short abuse, TR - Deformation of room under the weight of the system - personal injury - see 1.1.1/1.2.6	- Proper commissioning and service procedures	- Battery shutdown - Acoustic sensor to infer damage - see 1.1.1/1.2.6	2	3	5
2.4.17	Battery space	Enclosure	Fire	Battery system fire/electrical fire	- Total system failure - Total loss of battery capability - Loss of battery space (room) - Fire spread to adjacent rooms - Loss of vessel	- See 1.3.8/1.3.11	- See 1.3.8/1.3.11	2	5	7
2.4.18	Battery space	Enclosure	External fire	Fire in adjacent rooms	- Temperature rise in battery room - Possible for batteries to overheat (see 1.1.3/1.2.7/1.3.8/1.3.11-13/2.4.14)	- Follow hazard reduction plan for other rooms - Temperature monitoring in the battery room - Fireproof insulation (A60/A0) between rooms - independent ventilation system for battery room	- Emergency shutdown - Smoke and heat detection - Fire extinguishing system	3	3	6

Table 3 (cont.): Initial HAZID risk assessment of Li-ion BESS for marine applications.

Description of unit			Description of hazard					Risk (Initial)		
Ref. No.	**System Node**	**Element**	**Hazard**	**Cause(s)**	**Consequence(s)**	**Preventive Measures**	**Mitigating Measures**	**Freq. Class**	**Cons. class**	**Risk Rank**
2.4.19	Battery space	Enclosure	Non battery fire	- Electrical equipment - hybrid power source - arson	- Fire spreads to battery - Fire causes suppression system to activate - see 1.1.3/1.2.7/1.3.8/1.3.11-13/2.4.14)	- Battery space temperature and CCTV monitoring, alarms (before fire suppression) - Fire-resistant battery system casing - Minimise the number of fire risks in the room - Locate other power sources (e.g. engines) in another room	- Emergency shutdown - Smoke and heat detection - Fire extinguishing system - Fireproof insulation (A60/A0) to adjacent rooms	3	3	6
2.4.20	Battery space	Enclosure	Water ingress	- Sea water ingress through improperly placed/designed in/outlets - Condensation of water from cold sea air in the warm battery room - Structural damage, water penetration from above deck - Damaged water piping - Damage to water-based fire suppression	- Corrosion - Short circuits - hydrogen development (electrolysis of water) - See 1.3.12/1.1.2/1.2.4	- IP44 ventilation - IP44 boundaries - No unnecessary water pipework in the battery room - SOP for lifting/maintenance to prevent damage to pipes/fire suppression system - Appropriate structural integrity of deck	- independent battery ventilation - vent inlet into room away from the battery, no dripping - moisture sensors, drainage	3	3	6
2.5.21	Battery space	Ventilation	Gas accumulation	- Fan failure - Low air changes per hour - Lactation of ducts - Blockage - Structural damage	- Flammable and toxic gas build up (see 1.3.9/1.3.13) - Explosion in the duct	- Define minimum explosion resistance - vent openings at different heights for heavier than air off gas - Periodic function tests	- Emergency shutdown - explosion rupture disks	3	2	5

Table 3 (cont.): Initial HAZID risk assessment of Li-ion BESS for marine applications.

Description of unit			**Description of hazard**					**Risk (Initial)**		
Ref. No.	**System Node**	**Element**	**Hazard**	**Cause(s)**	**Consequence(s)**	**Preventive Measures**	**Mitigating Measures**	**Freq. Class**	**Cons. class**	**Risk Rank**
2.6.22	Battery space	Climate control	Over/under heating	- power failure - pump failure - blockage	- battery room overheat, slow warming of batteries if operational (no overheat of battery ref) - Battery room under heating leads to cold batteries if not operational - accelerated ageing	- Closed loop cooling - Operate vessel on partial battery (if only one battery room) or only with one battery room (if several battery rooms) - Safety critical power supply - Back up pump	- Emergency shutdown	4	1	5
2.4.23	Battery space	Enclosure	Submersion in water	- Collision - Capsizing	- battery TR failure (see 1.1.2/1.2.4) - Complete loss of battery capability (without TR failure) - Battery system needs full replacement	- Battery room above water line - Structural integrity - Battery room location	- CCTV, Fire alarm - Emergency shutdown - Pumps	1	4	5
2.7.24	Battery space	Fire suppression system	Fire not extinguished	- Failure of the system to operate - Inadequate system - pump failure - blockage - reignition - Sensor failure	- Fire spreads between racks - Loss of battery system - Loss of room/vessel	- periodic function tests - Fire extinguishing method tested before installation	- salt water extinguisher back up	3	5	8
2.7.25	Battery space	Fire suppression system	Fire not detected	- Sensor failure - Alarm ignored - No CCTV - Slow response	- Fire spreads between racks - Loss of battery system - Loss of room/vessel	- periodic function tests - Redundant sensors - Train personnel on LIB TR behaviour - IR sensors - Fast response sensors - Frequent maintenance	- Emergency shutdown	2	5	7
2.7.26	Battery space	Fire suppression system	Unsafe/ exacerbating actions of firefighters	- Delayed response of responders - Improper training/unaware of specific LIB hazards	- Exposure to toxic (HF) gas - Actions lead to an explosive atmosphere - Handling modules in unsafe manner	- Specific and periodic training - Standard emergency procedures - Specific teams for BESS ships - Explosive gas and HF measurements - Specific suits for HF	- Wait for trained personal	2	3	6

Table 3 (cont.): Initial HAZID risk assessment of Li-ion BESS for marine applications.

Description of unit			**Description of hazard**					**Risk (Initial)**		
Ref. No.	**System Node**	**Element**	**Hazard**	**Cause(s)**	**Consequence(s)**	**Preventive Measures**	**Mitigating Measures**	**Freq. Class**	**Cons. class**	**Risk Rank**
3.8.27	Electrical and control system	BMS and PMS	Failure	- Human error - Software error - Communication failure - Component failure	- electrical abuse (cell to rack) - temperature increase - see 1.1.2/3, 1.2.4/6	- System tested and verified - SOP	- Independent emergency shutdown - Rack/module based BMS - insulation between modules - Convertor protection - Enhanced observation and room cooling - Enclosure as heat sink	3	2	5
3.9.28	Electrical and control system	Converter	Converter failure	- Human or software error - Impact - Component failure - Loss of communication between convertor and BMS/PMS	- electrical abuse - temperature increase - see 1.1.2/3, 1.2.4/6	- System tested and verified - protection system - SOP	- Emergency shutdown - Insulation between modules - Temperature, voltage, current monitoring and alarms on all necessary systems	3	2	5
3.10.29	Electrical and control system	Emergency shutdown system	Failure	- Human error - Software error - Communication failure - Component failure	- electrical abuse - temperature increase - Continued operation and exacerbation of other hazards - see 1.1.2/3, 1.2.4/6	- System tested and verified - protection system - SOP	- Continued operation of cooling and thermal management - No load on battery - Temperature, voltage, current monitoring and alarms on all necessary systems	3	3	6

The battery system TR hazard (Ref. No. 1.1.1–1.1.3 and 1.2.4–1.2.7) has been separated based on cell or module level and on abuse type. As previous incidents have shown, electrical abuse is the most common cause of failure so assigned a higher frequency class than mechanical or thermal abuse, 3 rather than 2. On a cell level, the consequence of failure should be limited to the cell or its module, which can be isolated and easily replaced, leading to a consequence class of 2. As such, the overall risk rank of the cell TR hazard is broadly acceptable. However, at the module level, the consequence class increases (from 2 to 3) due to the larger potential energy release leading to the risk rank of module TR by electrical abuse requiring further analysis.

The fire hazard (Ref. No. 1.3.8) of the battery system has an unacceptable risk rank of 7 due to the high consequence category (5) with a frequency category of 2, this is also true for the enclosure (Ref. No. 1.4.17). The high consequence category assigned (greater than in [21]) is due to the fact that a battery system fire once initiated can quickly become very difficult to extinguish resulting in total BESS destruction and the vessel even with the preventative and mitigation methods in place. However, for a given ship with these measures in place, we would expect it to be a remote event.

Gas generation (Ref. No. 1.3.9) is possible due to the possibility of failure from a cell level up to the whole rack/system level. With correct procedures in place, the consequences would be major but limited to the battery space and the designated hazardous zone around the outlet of the ventilation system. However, the overall risk rank is 6 and therefore requires further consideration.

Due to the gas generation, the hazard of explosion on the battery system and enclosure (Ref. No. 1.3.10 and 2.4.14) can be catastrophic, leading to complete loss of the battery system, loss of structural integrity of the battery room and damage beyond the battery room that may lead to vessel loss. As more module or rack failures occur the rate and magnitude of gas generation significantly increase and can easily overcome the capabilities of the extraction system, as such it is likely the lower explosive limit (LEL) would be met. However, overall the likelihood of this event is remote and the resulting risk rank is 7.

Finally, at the battery system level, excess heat from electrical cabling (Ref. No. 1.3.11) is determined to be a broadly acceptable risk as it has a remote chance of occurrence and would lead to only minor system damage at the electrical cabling level. However, electrical arcing (Ref. No. 1.3.11) and HF gas generation (Ref. No. 1.3.13) are somewhat acceptable. Electrical arcing due to water-based fire suppression (as seen in the past) can lead to high temperatures and random failure propagation pathways which further exacerbates failure. Although damage would be major at a stem level it would be isolated to racks, but its occurrence is possible as the fire extinguishing system is activated by any fire source within the room and applied through the entire room. The possibility of HF production due to using a NOVEC gas fire suppression system is based on the frequency class of fire occurring. However, as HF is extremely toxic, with a low allowable exposure limit that can lead to life-changing injuries and death, the overall consequence is severe. Note, HF can also be produced in significant quantities by battery TR but is covered under the "Thermal Runaway" hazard of batteries (see "toxic species") in Table 3.

At the battery space level, structural failure hazards are present due to collision/grounding (Ref. No. 2.4.15) and design/installation errors (Ref. No. 2.4.16). These are deemed to be remote events as normal operation avoids collisions and guides for commissioning and servicing ensure proper installation. However, the consequence of collision/grounding is severe as it can lead to deformation of the room and associated safety systems, for example water/gas-tight integrity of the room and ventilation duct operability, affecting long-term safety and presenting possible hazards beyond the battery room, e.g. due to off-gas escaping into the vessel. Thus significant time would be required to check and repair the room even though battery operation may still be possible. In comparison, the consequence class of design/installation errors is less, at the major level, as it is expected to remain at the system level of the BESS.

Further, at the battery space level, fires in rooms adjacent to the battery room (Ref. No. 2.4.18) are somewhat acceptable due to being possible by the many external sources of fire, including traditional engine fires, but with damage on the battery enclosure remaining external and the battery system maintaining safe temperature conditions. Non-battery fires (Ref. No. 2.4.19) are at the same risk rank, but lower than battery fires, as it is expected that electrical fires are more easily extinguished and prevented from spreading to the battery system.

Water, by ingress (Ref. No. 2.4.20) and submersion (Ref. No. 2.4.23), also presents a hazard to the battery space. Experience has shown that water ingress through condensation of ventilation air or by seawater entering ventilation in/outlets can cause major damage from short-circuits and corrosion. Short circuits and corrosion are exacerbated by sea water ingress as a material's dielectric strength and insulation resistance reduce as relative humidity increases, while salt contamination increases surface conductivity and lowers breakdown voltage. Together, these effects compound and lead to accelerated degradation and insulation breakdown due to surface leakage, flashover, and material degradation. However, even with mitigation in place, due to the operational environment, this hazard is still possible and requires further consideration or to be addressed using ALARP. Submersion in water would lead to severe loss, however, this would only occur in the event of collision or capsizing so is an improbable event, so the overall risk is broadly acceptable.

Failure in environmental controls, leading to gas accumulation from ventilation faults (Ref. No. 2.5.21) or overheating from climate control faults (Ref. No. 2.6.22), leads to broadly acceptable risks. The failure of the ventilation system is possible in several ways, but with periodic system checks, this is minimised, while the consequences of the gas build-up will be confined to the battery space. A failure of the climate control system due to power loss or malfunction can occur occasionally, but with a quick response to minimise battery use or shut down the battery entirely then heat generation would be minimised and overheat prevented leading to minor damage.

A significant addition to the HAZID assessment is the consideration of the hazards related to the fire suppression system (Ref. No. 2.7.24–2.7.27). The failure to extinguish a battery fire (Ref. No. 2.7.24) has a frequency class of 3 because they are very difficult to suppress due to their housing preventing water from reaching the source of the fire, their ability to accelerate rapidly from module to rack and the ability of TR to re-initiate at a later unpredictable time. The consequence of this is level 5, for justification see Ref. No. 1.3.8/1.4.17, therefore overall the risk rank is 8 and not acceptable. A lack of fire detection (Ref. No. 2.7.25) due to sensor failure or an ignored alarm/slow response has a remote frequency of occurrence due to it being such a safety-critical system with redundancy. However, it can lead to total loss of the ship through a fire event (Ref. No. 1.3.8/1.4.17). Finally, ship personnel and firefighters (Ref. No. 2.7.26) can affect the ability to mitigate the severity of a battery fire leading to a risk rank of 7. With proper training, there is a remote frequency that the actions of the ship personnel or the firefighters will lead to a delayed response to the fire or mishandling of the event. However, as their actions can lead to the hazard of HF exposure or exacerbating fire and explosion hazards, the overall consequence is catastrophic as it can lead to loss of the room or vessel.

Considering the electrical and control systems, failure of the BMS/PMS or converter (Ref. No. 3.8.27/3.83.28) can lead to electrical and thermal abuse with the associated hazards as discussed earlier. This is determined to possibly occur but only lead to minor damage under existing preventative and mitigation methods. The failure of the emergency shutdown system (Ref. No. 3.8.29) may be possible due to human/software/hardware errors, but with the continued operation of the thermal management system and reducing the load on the battery damage will still be considerable, leading to an overall risk rank of 6.

The resulting risk ranks of Table 3 are summarised in the risk matrix of Fig. 6(a). Those with a risk rank of 6 or more, i.e. in the yellow and red bands, are analysed further (Section 5.1.2) to determine what current or future technologies can be applied to reduce their risk ranks.

5.1.2. Updated HAZID Analysis

The results of the updated HAZID analysis are summarised in Table 4 and discussed in detail in the following paragraphs.

The external short of modules (Ref. No. 1.2.4) in the past has been caused by coolant leakage, therefore if dielectric coolant is used instead of water-based coolants then shorts can be easily prevented even if leaks occur. Further, pressure sensors can be applied to monitor the liquid cooling system, and alert of pressure drops that could indicate leakages, thus providing an early warning for water-based coolant systems. The automotive industry shows a trend towards immersion liquid cooling (using dielectric fluids) that could also be applied to the marine sector to

	1. Improbable	2. Remote	3. Possible	4. Occasional	5. Fairly normal
5. Catastrophic		1.3.8, 1.3.10, 2.4.14, 2.4.17, 2.7.25	2.7.24		
4. Severe loss	2.4.23	1.3.13, 2.4.15			
3. Major damage		1.2.5, 1.2.6, 1.2.7, 2.4.16, 2.7.26	1.2.4, 1.3.9, 1.3.12, 2.4.18, 2.4.19, 2.4.20, 3.10.29		
2. Damage		1.1.1, 1.1.3, 1.3.11	1.1.2, 2.5.21, 3.8.27, 3.9.28		
1. Minor Damage				2.6.22	

(a)

	1. Improbable	2. Remote	3. Possible	4. Occasional	5. Fairly normal
5. Catastrophic	2.7.25	2.7.24			
4. Severe loss	2.4.23	1.3.8, 1.3.10, 2.4.14, 2.4.17			
3. Major damage		1.2.4, 1.2.5, 1.2.6, 1.2.7, 1.3.12, 1.3.13, 2.4.15, 2.4.16, 2.4.20, 2.7.26, 3.10.29			
2. Damage		1.1.1, 1.1.3, 1.3.11	1.1.2, 1.3.9, 2.4.18, 2.4.19, 2.5.21, 3.8.27, 3.9.28		
1. Minor Damage				2.6.22	

(b)

Figure 6: HAZID risk matrix (a) initial risk assessment, (b) final risk assessment after prospective mitigation measures updated.

provide better capacity for heat transfer under normal operation as well as under excessive heating (i.e. electrical abuse) minimising chances of over temperature. The commercialisation of all-solid-state Li-ion cells in the coming years also provides significant improvements against abuse and overall reduced heat generation on failure. With these improvements, where dielectric coolants, pressure sensors and immersion cooling are already commercially viable, the frequency of failure would be reduced from class 3 to 2, resulting in an updated risk rank that is now broadly acceptable.

A battery system fire (Ref. No. 1.3.8) can lead to catastrophic failure through module TRP and ignition of gases, hence the aim is to prevent/minimise the severity of these events. All-solid-state cells provide a greater resilience to TR and therefore TRP and eliminate the volatile and flammable liquid solvents [74, 75] reducing the severity of TR. The consequence of a battery system fire can also be reduced by improving TRP tests by conducting them without an operational BMS (as seen in previous incidents) or cooling system to represent a worst-case scenario where two significant safety features are inoperable. Further, safety improvements can be gained through accelerated learning by knowledge sharing of TRP testing by outlining registered testing bodies and having a centralised database of results. Extending from the module safety, the use of immersion cooling will also reduce the consequence of battery fire by helping to limit the propagation between racks. Finally, as suggested in the automotive industry [76], controlled discharge of modules/racks could help limit TRP. That is on the principle that if TR is detected in one module/rack, the nearest modules can be discharged rapidly into other modules within the battery to reduce the energy density around the module under failure, with the aim of preventing or reducing the severity of failure in the neighbouring modules. With these mitigations the consequence of failure could be limited to the battery system but still required significant downtime to replace a damaged system, resulting in a new consequence class of 4 and an overall risk rank of 6.

The gas generation hazard (Ref. No. 1.3.9) can be reduced with the use of solid-state cells due to the lack of liquid electrolytes. Further, a greater response to cell failure can be achieved by extending gas monitoring to include volatile organic compounds (VOC) and hydrocarbon sensing. VOC sensing (currently used in stationary storage [77]) is very useful as it can detect the release of electrolyte solvents that make up the majority of off-gas release on first venting [78], thus providing a warning at the earliest point of TR. The use of hydrocarbon monitoring is beneficial as the generation of H_2 and hydrocarbons can vary significantly, even for a given cell, under different abuse scenarios [14]. Thus, these coupled with the existing H_2 and CO monitoring can provide greater accuracy to the flammability risk of the air within the battery space. With this in place, the consequence of gas generation can be reduced by one point resulting in a new risk rank of 5.

The hazard from an explosion (Ref. No. 1.3.10/2.4.14) can be reduced through gas generation minimisation (as above) and through increased learning within the industry on off-gas composition and knowledge sharing. Further, testing of the ventilation integrity, and other systems, in the presence of an explosion is important to ensure that the system still works even after an explosion. This is because an explosion may be caused by the off-gas from the failure of part of the battery, while other parts still may be under failure (or fail later on) causing further gas generation and presenting further explosion hazard.

Further mitigation of electrical arcing (Ref. No. 1.3.12) can be achieved with segregated water suppression, whereby water is applied at individual rack level to prevent unnecessary water from being applied to non-failing racks thus minimising the chance that failure is exasperated away from the initiated failure point. This can be achieved through the controlled opening of water misters as well as using panels to separate racks and prevent water spreading, also having the advantage of minimising water usage. Further, direct water injection [79, 80] can be used to deal with modules on an individual basis. However, practically, this would have to be done manually by trained personnel, i.e. firefighters, and therefore would put people in harm's way while a response would be delayed while they are sought.

HF generation (Ref. No. 1.3.13) from NOVEC use is significant, as seen from the past incidents. NOVEC use can be eliminated by using an inert gas (CO_2 or N_2) to dilute the air in the battery room and suffocate fires. Minimising the production of HF reduces the consequence hazard, and results in a new risk rank of 5. However, there is the contradiction of gas suppression use (requiring a sealed room) and continuous ventilation (see "enhanced room ventilation" and dependence on LEL in Table 3) to prevent an explosive atmosphere. Therefore, it is recommended that the fire detection system should consider the gas sensing system (Ref. No. 1.3.9/1.3.10/2.4.14) for detecting flammable gases from battery failure. In this way, a distinction can be made between a non-battery fire (i.e. electrical fire) that can be suffocated by dilution without risk of explosion, and battery failure leading to the production of flammable gasses that need to be ventilated. Inert gases can still be used in this scenario to dilute the vent gas as it is extracted to reduce the potential of ignition.

Note, HF is also produced by the batteries themselves when under TR. This source of HF can be minimised by using cells with non-fluorinated materials [81–83]. However, the main fluorinated component in common cells is the $LiPF_6$ lithium salt within the electrolyte, chosen for it superior electrochemical performance. Hence, choosing an alternative to this may come with performance sacrifices.

Structural failure of the enclosure (Ref. No. 2.4.15) can be further mitigated by studies, most practically by computational simulations, to determine that structural integrity can be maintained and racks are not dislodged.

To reduce the hazard of enclosure fire (Ref. No. 2.4.17) it is required to keep the fire at the level of the room and prevent vessel loss. As with (Ref. No. 1.3.8), solid-state cells and immersion liquid cooling reduce the overall risk of going into TR. However, as Li-ion fires can last significant amounts of time and require lots of water to maintain cooling [84–86] a backup using seawater (in addition to the fresh water system [21]) would allow continued cooling and prevent temperatures that compromise the integrity of the battery room.

To further reduce the hazard of external fires (Ref. No. 2.4.18) considerations should be given to sizing climate control systems so that they can deal with excess heat being transferred into the room that would be beyond that normally generated by the battery system. Additionally, as solid-state cells have higher safety temperatures [74, 75], in the event of excess heat, there would be more time put out the external fire.

Non-battery fires (Ref. No. 2.4.19) can be further mitigated using direct fire suppression increasing the efficiency of fire suppression thus minimising the chance of fire spreading to the battery whilst also minimising the possibility of water damage to the battery. Further, fire and radiation shields can be placed between high-risk heat sources and the battery system to minimise the possibility of fire spread.

The hazard of water ingress (Ref. No. 2.4.20) can be further reduced by undertaking periodical checks of high-risk areas to determine if there is water ingress/development, build-up of salt deposits or noticeable degradation of insulators or corrosion of material. Through this, operators can rectify an issue before it develops into a more serious problem. . Further investigation is recommended to assess the long-term effects of humidity and salt on battery system degradation and corrosion. Including determining if the battery bus voltage of approximately 1200V DC presents a hazard regarding insulation breakdown voltage in this harsh environment.

Minimising the chance that a fire is not extinguished (Ref. No. 2.7.24) can be aided by the use of direct injection suppression, with the difficulties as discussed earlier, or by using a dual water/gas system with saltwater suppression backup on a septate pump system. This also aligns with the additional mitigations of hazard 2.4.19.

Not detecting a fire (Ref. No. 2.7.25) is remote, but as experience has shown, it is possible. Therefore, in addition to fire detectors, (heat/smoke) gas detectors used for the gas/explosion hazard, especially the VOC sensors can be used as an early warning of a possible fire [87, 88]. The use of CCTV and machine learning image recognition software (for identification of smoke/flames) can add the ability to raise an alarm from visual images without personnel continually monitoring the video feed [89, 90].

Reducing the likelihood of emergency shutdown failure (Ref. No. 3.10.29) can be achieved with operating procedures dictating that periodic function tests should be carried out, and that a direct method to shut down the system (i.e. not remote from the bridge) is accessible in an emergency and resilient from impeding battery fires for a significant time.

Digital twins and associated intelligent operation & maintenance have the potential to reduce the frequency of several of the hazards associated with the BMS, TMS, PMS, climate control and emergency systems (see Table 3). These systems rely on numerous sensors, making them inherently well-suited for integration with a digital twin, which can provide the necessary data to enhance performance, optimise control, and improve overall safety and efficiency [91]. However, the basis of a digital twin requires a robust representation of physical processes. In the battery field, capturing degradation and the early stages of TR is difficult [92], and models still need to be improved. Hence, a digital twin's performance for improving battery safety still needs to be tested; as such, its impact on reducing risk is not included in Table 4.

5.1.3. Summary

Following these additional mitigation measures the 15 medium/high risks have been reduced to 6 medium risks, see Fig. 6(b), which can be allowable under the ALARP method. This HAZID is a high-level risk analysis where the hazards of BESS TR and battery space failure (i.e. room and fire suppression defects, and so on) are identified as major sources of risk. As such, these are analysed further using the Bow-tie methodology in the next section to analyse in detail the controls, barriers and escalating factors that affect these events.

5.2. Bow-tie Analysis of Major Hazards

The failure of the BESS is fundamentally from mechanical, electrical or thermal abuse, however, as Table 1 and Table 3 show, electrical abuse is most prominent and as such will be considered as the top event of the BESS TR hazard. For the hazard of battery space failure, the top event is considered to be the TR failure of the BESS.

The bow-tie analysis is carried out as under common practice [27], a hazardous event is placed in the middle of the bow-tie diagram, while causes (hazards/threats that may lead to the event) and consequences are placed on the left and right respectively. From this, an accident scenario follows any of the lines/paths from an initiating event to an end state, which is used for establishing the consequence spectrum. Along a path, an enabling event can trigger an initiating event or enable an accident scenario further down the path (closer to the accident). Enabling events are

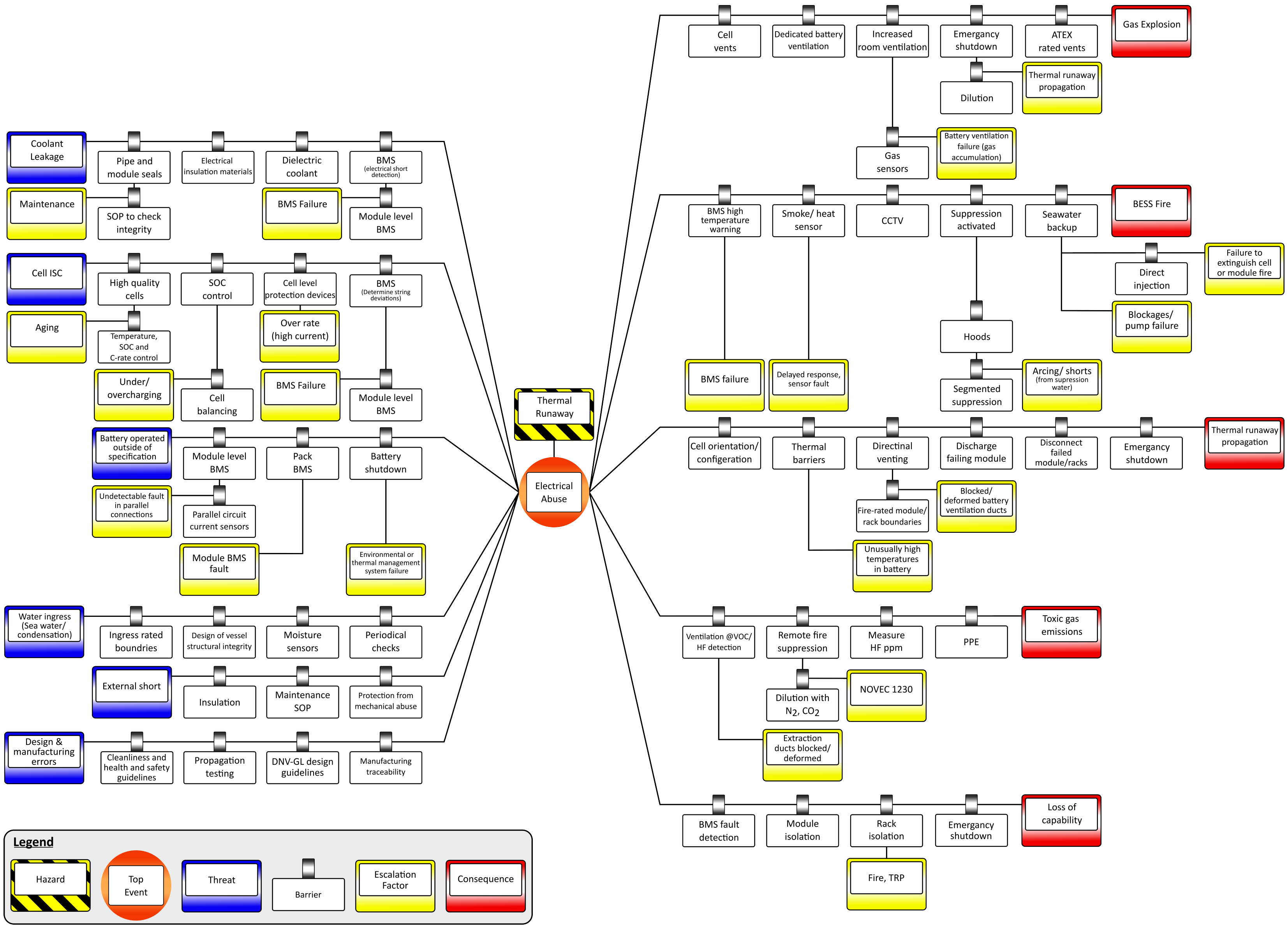
Table 4: Updated risk mitigation to address medium and high risk hazards of Fig. 6(a), yellow and red hazards respectively.

	Risk (Initial)				**Risk (Final)**		
Ref. No.	**Freq. Class**	**Cons. class**	**Risk Rank**	**Risk Prevention/Mitigation**	**Freq. Class**	**Cons. class**	**Risk Rank**
1.1.1	2	2	4	n/a	2	2	4
1.1.2	3	2	5	n/a	3	2	5
1.1.3	2	2	4	n/a	2	2	4
1.2.4	3	3	6	• Dielectric coolant. • (fluid) pressure sensor. Solid state cells. • Immersion liquid cooling	2	3	5
1.2.5	2	3	5	n/a	2	3	5
1.2.6	2	3	5	n/a	2	3	5
1.2.7	2	3	5	n/a	2	3	5
1.3.8	2	5	7	• Solid state cells • TRP test without BMS/coolant, open database • Dump rack energy • Immersion liquid cooling	2	4	6
1.3.9	3	3	6	• Solid state cells • VOC, Hydrocarbon sensing • Prismatic cells	3	2	5
1.3.10	2	5	7	• VOC senseing • (knowledge) increased testing/open database • Test ventilation integrity	2	4	6
1.3.11	2	2	4	n/a	2	2	4
1.3.12	3	3	6	• Compartmentalisation of racks • Segregated water suppression	2	3	5
1.3.13	2	4	6	• Use CO_2 or N_2	2	3	5
2.4.14	2	5	7	• VOC senseing • (knowledge) increased testing/open database	2	4	6
2.4.15	2	4	6	• Experimental/simulation studies to determine integrity	2	3	5
2.4.16	2	3	5	n/a	2	3	5
2.4.17	2	5	7	• Solid state cells • Immersion liquid cooling • Salt water back up to maintain cooling	2	4	6
2.4.18	3	3	6	• Supplementary climate control (Cooling) • Solid state cells	3	2	5
2.4.19	3	3	6	• Direct fire suppression • Radiation insulation between electrical equipment and BESS	3	2	5
2.4.20	3	3	6	• Periodical checks	2	3	5
2.5.21	3	2	5	n/a	3	2	5
2.6.22	4	1	5	n/a	4	1	5
2.4.23	1	4	5	n/a	1	4	5
2.7.24	3	5	8	• Direct injection • Dual system water and gas	2	5	7
2.7.25	2	5	7	• CCTV (image recognition)	1	5	6
2.7.26	2	3	5	n/a	2	3	5
3.8.27	3	2	5	n/a	3	2	5
3.9.28	3	2	5	n/a	3	2	5
3.10.29	3	3	6	• Periodic function tests • Direct/local back up	2	3	5

off the “main path” of the scenario but increase the probability of an event in the sequence occurring. From this, it is then possible to see the full path from cause to consequence, at what point existing barriers play their role in preventing/mitigating risk and where additional or enhanced barriers should go.

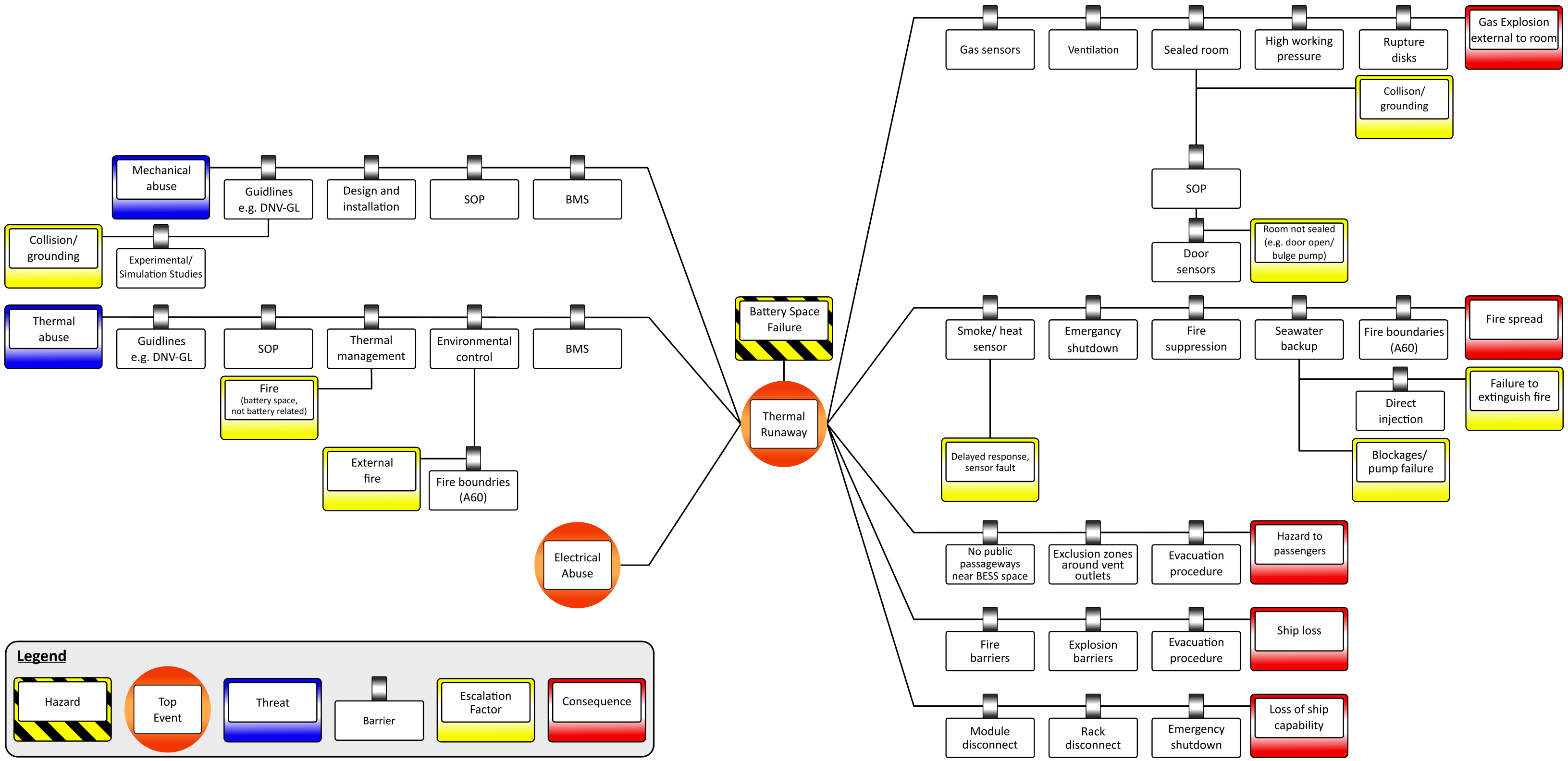
5.2.1. Bow-tie Results

Following the theory above, and from the learnings of the HAZID analysis (see Section 5.1.1 and Tables 3 and 4), the resulting bow-tie analyses for the TR and battery space hazards are presented in Figs. 7(a) and 7(b) and discussed in the following Sections 5.2.2 and 5.2.3, respectively.



(a) Thermal runaway hazard due to electrical abuse.

Figure 7: Bow-tie analysis.



(b) Battery space failure hazard due to thermal runaway.

Figure 7: Bow-tie analysis.

5.2.2. Discussion of Thermal Runaway due to Electrical Abuse

5.2.2.1 Threats Leading to Electrical Abuse

The main threats identified that can lead to electrical abuse are: (1) coolant leakage from the thermal management system of the battery module and cells for liquid-based channel cooling; (2) cell internal short circuits (ISC) that can be soft or hard and recoverable or non-recoverable occurring due to, or exacerbated by, imperfections, manufacturing defects and cell conditions; (3) battery operating conditions leading to operation outside the design safe operating window, which maybe due to operator requirements or factors affecting equipment capability e.g. overcharging due to BMS failure or poor cell balancing procedures; (4) water ingress from the condensation of moisture from external air entering the battery room, or seawater directly entering the room, via the ventilation system; (5) external electrical short of the battery or its subcomponents by other means other than water/coolant; and (6) design and manufacturing errors that lead to inherent faults.

5.2.2.2 Consequences of Electrical Abuse

The main consequences leading from electrical abuse are: (1) Thermal runaway propagation from the cell, to the module, through to the BESS system, exacerbated by hot vent gasses and flame generation; (2) BESS fires that generate significant and prolonged burning that is difficult to extinguish; (3) Gas explosion due to the generation, accumulation and ignition of flammable gases that do not get consumed by a battery fire; (4) Toxic gas emissions, namely HF, from the battery failure or fluorinated containing (e.g. NOVEC-1230) gas based fire suppression system; and (5) Loss of capability as a module or the whole battery fails or is shutdown for safety. These consequences are the same for other types of abuse, i.e. mechanical and thermal, and as such can be used in the analysis of these top events with appropriate threats and preventative barriers.

Threats beyond the boundary of the battery (but not considered in this analysis) include threats to the wider ship, personnel and passengers, and environmental damage, due to the flammable and toxic gas emissions that are vented from the room.

5.2.2.3 Prevention Barriers of Electrical Abuse

The barriers to preventing electrical abuse can be broadly categorized into (1) *battery and battery control*, and (2) *equipment integrity* measures. First, within the battery measures, is the selection of high-quality cells that have minimal variation between each other, for example, the cell internal resistance that can affect long-term health and ageing characteristics affecting cell imbalances. Further, high-quality cells will suffer less from manufacturing defects such as burrs, cracks in the separator, electrode cavities, metal particle contamination and separator misalignment, all of which affect the chance and severity of an ISC developing [93]. Additionally, cell-level protection such as current interrupt devices, positive temperature coefficient resistors and vents can help in preventing high currents, temperatures and pressures, respectively, in the cell [94].

Following this, correct configuration and sensing of the battery and its sub-levels are needed to maintain a safe SOC window, C-rate and temperature at each level. A BMS, and module-level BMSs, along with a thermal management system not only maintain these safety parameters in the moment but prevent undue cell ageing that affects long-term safety and performance [95, 96]. The BMS also interprets the voltage, current, temperature, pressure and gas sensors for fault detection. The correct configuration of voltage and current sensors is required to allow the identification of cell ISC or sensor faults in series and parallel connections whilst minimising the number of required sensors [97, 98]. The BMS is also required to perform cell balancing so that over/under-charging does not occur within parallel strings [99]. As can be seen in Fig. 7(a), the BMS is integral to many of the barriers, while using module-level BMS allows for redundancy and fault detection at a higher level. Ultimately, the BMS warns of events/conditions that mean that the battery should be shut down to maintain safety.

Equipment integrity measures fundamentally ensure the soundness of the system based on effective design, manufacturing and installation of the system that has been implemented according to appropriate guidelines e.g. DNV-GL [21]. More specifically, related to electrical abuse, the prevention of external shorts requires electrical insulation of cell/module terminals; standard operating procedures (SOPs) for maintenance to prevent damage or the use of tools that could lead to shorts; and protection from sources of mechanical abuse, e.g. vibrations that lead to connections coming loose. The barriers to prevent shorts from water ingress are again built on fundamental design measures, ingress boundaries and structural integrity that prevent (1) seawater entering the battery through ventilation inlet/outlets, (2) condensation onto the battery due to the cooling air of the environmental control system and (3) water leaks from above deck. Additional barriers can be put in place to monitor the moisture in high-risk areas as well as periodical checks by the personnel to determine if there is water pooling in high-risk areas.

5.2.2.4 Mitigation Barriers of Electrical Abuse

Mitigation of electrical abuse can be categorised into (1) *secondary protection*, and (2) *emergency response* measures. Secondary protection is required to prevent a fault from escalating, for example from a cell to module level failure, to mitigate TRP and also to reduce the amount of functional capacity loss (i.e. minimising the number of modules/racks disconnected).

The emergency response barriers play the most significant role in the mitigation of fire, gas explosion and toxicity hazards. The first step in fire mitigation is detection, based on BMS, smoke sensors and CCTV at increasing barrier levels for the activation of the fire suppression. The design of the fire suppression system should consider that the water released may lead to arcing, therefore segmented suppression (i.e. on a rack level) is beneficial to reduce the chance of secondary hazards. Further, considering that battery fires are known to proceed for a long time, having the ability to use seawater as a backup (if the freshwater supply runs out) allows for continued cooling. Mitigation of gas explosions requires the ability to detect an explosive atmosphere and increase ventilation capacity to prevent it from reaching the lower explosive limit or can be diluted with an inert gas (if LEL exceeds allowable thresholds within a closed system), where explosive atmosphere (ATEX) rated ventilation systems are in place so that their operation does not cause ignition. Similarly, toxicity can be mitigated first by the detection of toxic gases released from battery failure, followed by increased ventilation. Significantly, consideration of not using fluorinated gas suppression systems (e.g. NOVEC-1230) drastically reduces HF hazard but affects fire suppression ability. Finally, personal measures are required to quantify the HF contamination level to determine if PPE should be worn when approaching the battery after an event.

5.2.3. Discussion of Battery Space Failure due to Thermal Runaway

5.2.3.1 Threats Leading to Battery Thermal Runaway

The main threats leading to Battery TR are: (1) electrical abuse, as discussed in Section 5.2.2 and Fig. 7(a); (2) mechanical abuse that can occur during installation, operation or maintenance, exacerbated by the chance of collision or grounding, which will involve significant force and vibrations with possible damage to the fundamental fabric of the battery room; and (3) thermal abuse, exacerbated by fires internal or external to the battery room.

5.2.3.2 Consequences of Battery Thermal Runaway

The main consequences leading from battery TR are: (1) fire spreading from the battery to auxiliary equipment in the room or to rooms adjacent to the battery space, which may escalate due to sensor failure and resulting delayed response, suppression system failures leading to the fire not being extinguished; (2) gas explosion occurring external to the battery room or outside the designated exclusions zones around outlet vents, exacerbated by the room not being sealed (door left open/bulge pump piping) or by a collision compromising the gas-tight boundary of the room; (3) hazards to passengers, from fire, toxicity and explosions; (4) loss of ship capability (performance); and (5) the complete loss of the ship.

5.2.3.3 Prevention Barriers of Battery Thermal Runaway

The preventative barriers of TR from electrical abuse are discussed in Section 5.2.2.3. The barriers to mechanical and thermal abuse are broadly similar, based on governing body guidelines, proper design and installation, SOPs and, as with electrical abuse, the use of the BMS for fault detection. Specific to mechanical abuse is the use of experimental or simulation methods to understand the effects of abuse scenarios, such as collision, on the structural integrity of the battery and the battery room. While, for thermal abuse, the design of the battery thermal management system and battery room environmental controls, aided by sufficient fire boundaries, is crucial to maintaining safe operating temperatures.

5.2.3.4 Mitigation Barriers of Battery Thermal Runaway

Similar to electrical abuse, the mitigation to battery TR can be categorised into (1) *secondary protection*, and (2) *emergency response* measures. Secondary protection, in this case, includes, for the mitigation of gas explosion, confining the gas to the battery room and controlling its path through a ventilation system or burst disks that allow the overpressure to expand in a controlled manner in a chosen direction. Mitigation of the fire spread builds on the same barriers on the battery level but with sufficient fire boundaries (i.e. A60 fireproof thermal material) between the room and neighbouring rooms. To mitigate the hazards to passengers, there should be no public passageways near the BESS room or the exclusion zones of the vent outlets. The emergency response measures are based on the detection and suppression of the fire, ship-specific and clear evacuation procedures for passengers and personnel, along with SOP for the battery disconnection and emergency shutdown.

5.2.4. Summary

The bow tie analysis shows that the BMS is an integral preventative barrier for several of the threat pathways under both electrical abuse and thermal runaway events. Moreover, for the electrical abuse event, cell selection is an important barrier for long-term safety, while equipment integrity is a barrier to the remaining threat pathways. For the thermal abuse event, the main barriers are broadly categorised as guidelines, proper design and installation, and well-defined SOPs. On the mitigation side, for both events, secondary protection and emergency response measures are the critical barriers. Consequences of electrical abuse lead to fire, explosion and toxicity hazards which are greater for the TR event. Similarly, the loss of ship capability increases between the electrical abuse event and TR events, and additionally there are significant consequences of hazard to passengers, total ship loss and total loss of ship capability for the TR event.

5.3. *Considerations for Industry*

As shown through the above risk assessment, several technologies can be utilised to increase safety, including dielectric coolant, immersion cooling, solid-state cells, VOC sensing, segregated or directional suppression, machine learning and digital twins, and inert gas suppression. However, for the marine sector to benefit from these technologies they must lead the way in evaluating their benefits through dedicated studies, or otherwise risk lagging behind while waiting for developments to be made in the automotive and grid scale sector. Further, significant improvements can be made, not only in the marine sector, but also the wider battery field through more open practices. There needs to be a greater understanding of the fire hazard in terms of the types and quantities of gasses produced and the heat release rate from fire. This data can be collected according to *UL 9540A* for "Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems" [73]. However, the data from these tests is not readily available, while similar data from academic literature is limited to systems less than a few tens of kW h [14]. With such data, probabilistic models could be developed for gas release rates and heat release rates which would significantly help future risk assessments by allowing the severity of hazards to estimated, in turn improving the definition of vent duct, fire suppression system and thermal/radiation barrier requirements.

6. Conclusions

The adoption of large LIBs for primary propulsion and auxiliary power in the electrification of shipping is rapidly increasing. However, the TR of LIBs in marine applications poses unique threats and challenges over those used in automotive EV and stationary applications. Considering past incidents, analysed in this work, the most prominent cause of TR was by short circuit related to water wherein half were related to coolant leakage. Further, most incidents lead to fire or explosion, indicating that the barriers to stop escalation to TRP were not effective. Key areas of learning from past incidents have been made in fault detection, fire suppression/fighting, gas generation and LIB safety knowledge.

Following this, HAZID analysis was carried out considering the battery system, the battery space and the electronic system where on initial assessment there were 14 broadly acceptable risks, 14 ALARP risks and 1 unacceptable risk. After, assessing the use of transferable technologies (from automotive and stationary storage sectors) and future technologies risk were reduced to 23, 6 and 0 broadly acceptable risks, ALARP risks and unacceptable risks, respectively.

Bow-tie analysis was carried out on the most concerning events, an electrical abuse event leading to the TR hazard and a TR event leading to the battery space failure hazard. It was shown that preventative barriers to electrical abuse could be categorised into *battery and battery control*, and *equipment integrity* measures. For the TR top event, the preventative barriers were governing body guidelines, proper design and installation, SOPs and the BMS. For both top events barriers were categorised as *secondary protection* and *emergency response* measures. The analysis showed the increase in the scale of hazards from the electrical abuse to the TR event, as the failure of the battery room can lead to full loss of capability, hazards to passengers, and complete ship loss.

Updated guidelines based on the insights gained from studying past incidents have led to better safety practices for the marine Li-ion BESS sector, however, as shown here there are still improvements to be made by using transferable and future technologies. These technologies should be quantitatively assessed by academia and industry alike to determine their effectiveness in hazard reduction for ongoing safety improvements. Industry should also focus on making the results of their TRP testing public (even if anonymous), so that a larger data set can be complied for predicting variation in fire behaviour. With this, further research should be undertaken on risk reduction technologies (i.e. those discussed herein as well as new ones) whilst engaging in multi-disciplinary collaborations such as marine engineering and safety sciences to be able to design technologies with the best consideration to applications and safety assessment.

Conflicts of interest

There are no conflicts to declare.

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