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BattFiSafe23

Developing battery fire safety requirements suitable for smaller EES spaces onboard

A prestudy carried out within the Swedish Transport Administration's industry program Sustainable Shipping, operated by Lighthouse, published in March 2025

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Developing battery fire safety requirements suitable for smaller EES spaces onboard.

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In cooperation with
Marioff & Candela

A prestudy carried out within the Swedish Transport Administration's industry program Sustainable Shipping, operated by Lighthouse

Summary

The project “BattFiSafe 24” is a pre-study aimed at investigating fire test requirements for water-based fire extinguishing systems and adapted rule requirements for battery installations in small electric energy storage (EES) spaces on board ships. The objective of the project was to provide a comprehensive review of current firefighting practices for lithium-ion battery (LIB) fires, drawing from scientific literature and industry pre-studies. The project collaborated with manufacturers through workshops to enhance knowledge of firefighting systems for confined maritime spaces. The project aimed to draft a proposal for test specifications and a foundation for future studies to verify the effectiveness of these systems in preventing thermal propagation in LIBs.

The project entailed close collaboration with industry partners, experts in the maritime domain, and battery fire safety. To gather input, and discuss firefighting systems and relevant regulatory aspects, a literature study, and a workshop were conducted. The project outcomes identified the limitations of water mist systems in confined spaces and highlighted the potential benefits of water flooding systems, particularly those designed to flood inside battery packs. Innovative solutions, such as enclosing battery packs in open-top boxes, were considered to optimize water usage and enhance cooling effects. Several recommendations were made based on the results including the integration of different suppression methods, efficient water usage, rigorous testing of new designs, and adaptability to confined spaces. By addressing safety considerations and implementing clearer functional requirements, more fit-for-purpose standards can be developed, and the safety and reliability of firefighting systems in small EES spaces can be enhanced.

Sammanfattning

Projektet "BattFiSafe 24" är en förstudie som syftade till att undersöka brandtestkrav för vattenbaserade brandsläckningssystem och anpassade regelkrav för batteriinstallationer i små elektriska energilagringsutrymmen (EES) ombord på fartyg. Projektets mål var att ge en omfattande översikt över nuvarande brandsläckningsmetoder för bränder i litiumjonbatterier (LIB), baserat på vetenskaplig litteratur och industriförstudier. Projektet samarbetade med tillverkare genom workshops för att förbättra kunskapen om brandsläckningssystem för trånga maritima utrymmen. Projektet syftade till att utarbeta ett förslag till testspecifikationer och en grund för framtida studier för att verifiera effektiviteten av dessa system i att förhindra termisk spridning i LIB.

Projektet innebar nära samarbete med industripartners, experter inom det maritima området och batteribrandsäkerhet. För att samla in synpunkter och diskutera brandsläckningssystem och relevanta regleringsaspekter har en litteraturstudie, och en workshop genomfördes. Projektets resultat identifierade begränsningarna hos vattendimsystem i trånga utrymmen och lyfte fram de potentiella fördelarna med vattenflödessystem, särskilt de som är utformade för att flöda inuti batteripaket. Innovativa lösningar, såsom att omsluta batteripaket i öppna lådor, övervägdes för att optimera vattenanvändningen och förbättra kyleffekterna. Ett antal rekommendationer gjordes baserat på resultaten, inklusive integration av olika släckmetoder, effektiv vattenanvändning, noggrann testning av nya konstruktioner och anpassningsförmåga till trånga utrymmen. Genom att ta itu med säkerhetsaspekter och implementera tydligare funktionskrav kan mer ändamålsenliga standarder utvecklas, och säkerheten och tillförlitligheten hos brandsläckningssystem i små EES-utrymmen kan förbättras.

Contents

1 Introduction

The latest rules and guidelines with regards to fire safety of electric energy storage (EES) spaces on board ships are developed for vessels engaged in international and domestic shipping. These ships normally have plenty of space for the battery installation [1], which makes an installation of water mist fire extinguishing system possible according to International Maritime Organization (IMO) MSC/Circ.1165. In all the latest rules and guidelines [1], [2], [3], water mist systems are required to fulfil IMO MSC/Circ.1165. It has been assumed that these systems have enough cooling capacity for installed batteries with capacity up to 5 MWh.

It shall be noted that IMO MSC/Circ.1165 is developed for fire extinguishment of flammable liquids and gases in machinery spaces and not for EES spaces with, for example, battery installation. For smaller ships, installing extinguishing systems in accordance with IMO MSC/Circ.1165 will result in an over-designed system relative to the amount of installed energy. Additionally, it is not feasible to meet the requirements to the full extent due to the limited space available onboard. By developing functional requirements for fire suppression systems for small ships, fire safety can be secured. This will accelerate the pace of decarbonization for smaller vessels.

1.1 Purpose of the study

This pre-study aims to investigate relevant fire test requirements for equivalent water-based fire extinguishing systems and adapted rule requirements for battery installations in small EES spaces on board.

The investigation will generate a "helicopter" perspective on state-of-the-art firefighting practices for lithium-ion battery (LIB) fires through a review of scientific literature and pre-studies from the maritime sector as well as other industry sectors.

In collaboration with manufacturers during workshops, the study will increase knowledge of adapted firefighting systems for battery installations in confined spaces for smaller maritime tonnage.

The result will be a draft proposal for test specifications for suppression systems. The study will also lay the groundwork for future studies that can verify proposed test specifications and suppression systems' effectiveness of thermal propagation in LIB.

2 Background

In this section, LIB systems and their maritime applications will be introduced, along with the introduction of LIBs on smaller vessels. Following the introduction, the fire hazards associated with LIB systems will be presented, along with firefighting methods and their effectiveness, safety implications, and limitations. The most relevant international regulations pertaining to battery fire safety in the maritime industry will be presented, followed by a discussion of areas for future research.

2.1 Lithium-Ion Battery Systems and Their Maritime Applications

Lithium-Ion batteries (LIB) have today altered the maritime sector and formed a central part in next generation power systems. Their high voltage capability combined with high energy density, light weight, low self-discharge, and long lifespan for storing electrical energy have made LIBs attractive for various applications within maritime transport [5, 8].

A battery system normally consists of several battery packs which have their own protective housing and are composed by battery modules which themselves consist of battery cells connected in series and/or parallel configurations. The cell itself consists of a cathode, anode, separator, electrolyte and current collectors.

The maritime applications of LIB systems are diverse and rapidly developing. Ranging from onboard electricity to auxiliary power, hybrid propulsion, and full propulsion, LIB systems are used in a variety of ways in terms of their onboard function and how they are utilized. Depending on the industry segment and vessel size, functional applications of these batteries include spinning reserve, peak shaving, optimizing load, and immediate power, to harvesting energy, and backup power [8].

Rules and guidelines are currently evolving and are being developed to cover all safety aspects of this relatively new technology. Classification societies such as DNV, Bureau Veritas (BV), and Lloyd's Register (LR) have published rules, and regulators such as European Maritime Safety Agency (EMSA) and the Swedish Transport Agency are currently developing guidelines [12]. When it comes to requirements for water-based fire extinguishing systems, the most applicable regulation is the International Maritime Organization's (IMO) MSC/Circ. 1165 which will be introduced in more details in a following subsection.

The current high energy density of the available battery systems makes them an appropriate option for short distance voyages or services. For smaller ships operating in national trade, electrification using LIB systems is presently the preferred choice in their goal to reach net zero emissions. On the other hand, the flammable electrolytes deployed in LIBs pose questions regarding fire safety, making this study important for the pursuit of decarbonization in certain segments of the maritime industry [4, 8].

2.2 LIB Systems on Smaller Vessels

LIB systems are becoming increasingly relevant for smaller maritime tonnage and short-sea shipping, which refers to shipping operations in national waters or short international voyages [7]. The vessels active in these services are typically smaller than those used in conventional international shipping. According to DNV, vessels under 15 meters in length overall (LOA) are defined as "small craft."

Space and weight limitations introduce challenges for the design and operation of these smaller vessels. Limited available space leads to smaller EES spaces, introducing safety implications that merit special attention [16]. Acknowledging this safety concern, the Norwegian Maritime Authority has proposed limitations on the amount of gas and heat produced as a result of cell failures onboard ships that are under 24 meters in length [17]. However, the effect of close proximity of cells on the propagation of battery fires is not completely understood in research [18]. Fire hazards associated with battery power onboard will be presented in more detail in the next subsection.

Another fire safety implication for vessels engaged in short-sea shipping relates to their operation. For ships on short coastal voyages, the fire safety strategy may include evacuating crew and passengers to a safe location and relying on onshore firefighting services, depending on their availability and readiness [6]. These considerations call for closer attention to this growing sector and the development of guidelines and regulations that are fit for purpose.

When electrifying smaller crafts, it is crucial to build them as light as possible to maximize their range. Consequently, these vessels are often constructed with fire-sensitive material, necessitating fire suppression systems with excellent heat-absorbing properties to protect their EES spaces. Examples of fully electric smaller vessels that operate over short distances for passenger transport include Candela's P-12, Hyke's Shuttle, Brødrene Aa's Estelle, and Seabubble's Smart Bubble, and Yinson's Hydroglyder. Common to all vessels of this type is the very limited size of the EES space. These spaces are often so small that a person cannot enter them. More detailed specifications of these vessels are summarized in Table 1.

Table 1. Small passenger crafts employing battery power [19, 20, 21, 22, 23, 24, 25, 26, 27, 28].

Ship Name	Builder	LOA [m]	Battery Size [kWh]	Structural Material	Operation
P-12	Candela	11.99	4 × 63	Carbon Fiber	Stockholm - Ekerö, passenger ferry
Shuttle 0001	Hyke	15	95-285	Glass Fibre	Fredrikstad, Norway, urban passenger ferry,
Estelle	Brødrene Aa	12	188	Carbon Fiber Sandwich	Riddarfjärden, Stockholm
Smart Bubble	Seabubbles	8	90-130	Carbon Fiber	Lake Annecy, France, shuttle service
Hydroglyder	Yinson	11.9	252	E-glass Sandwich Foam Core	Singapore, crew transfer
EF-12	Artemis	12	412	Carbon Fiber Sandwich	Port of Gothenburg Pilot boat from 2026

Smaller EES spaces and the associated fire hazards are not limited only to smaller vessels engaged in short-sea shipping. As the safety concerns described above relate to space constraints for batteries rather than ship size or operations, the results of this study can be significant for ships of various tonnage in different sectors (smaller EES spaces can also be found on larger ships).

2.3 Fire hazards

There are several fire safety concerns associated with LIBs onboard including thermal runaway, electrolyte gas venting, fire, and explosion [5]. The biggest hazard associated with lithium-ion batteries is thermal runaway. Thermal runaway is a non-reversible state of rapid self-heating, where a series of exothermic chemical reactions are initiated following a temperature increase in the battery cell [1, 3, 9].

In many instances these risks are present in combination. Thermal runaways are typically introduced through mechanical, thermal, or electric abuse. Internal manufacturing defects such as material defects, construction flaws or contamination as well as physical abuse such as mechanical damage or external fire can cause battery fires. Excessive cold and overheating the battery system and electrical abuse such as over-charging, over-discharging, overcurrent and external short circuit can also cause fire safety concerns [1, 4].

Fires in LIBs are notoriously challenging to extinguish, primarily because of the protective casings designed to shield the battery from external factors such as moisture among others. Additionally, these casings are typically rated with an IP (Ingress Protection) classification, indicating their resistance to both particles and liquids, which further complicates firefighting efforts. Even though thermal runaway in one battery cell may not be an integral safety threat to a ship, the risk of propagation to adjacent cells is a significant safety hazard [3]. Thermal runaway fires are complex and involve multiple categories of fire [1]. There is also fire hazards associated with the off-gas produced during thermal runaway. This off-gas is highly flammable and toxic [13], but it is worth noting that the toxicity is not significantly more than that of plastic fires [4].

2.4 Firefighting Systems

Various solutions including protection, detection, suppression and extinguishing are used to increase the fire safety of lithium-ion battery installations [1]. Comprehensive Battery Management Systems (BMS) are crucial as a protective measure against thermal, and electrical abuse through monitoring and controlling voltage, current, temperature, and state of charge [9]. Passive measures of fire protection designed to contain and prevent the spread of battery fire include the use of a dedicated battery space, separation distancing between packs, fire walls between cell packs, and the use of Phase Change Materials (PCM) that can function as buffer and conductor for effective thermal management [1, 9, 14].

Suppression and extinguishing systems consist of different types of systems and agents as identified below:

- Gaseous fire extinguishing systems
- Condensed aerosol systems
- Water mist systems
- Automatic sprinkler systems
- Water deluge systems
- Foam systems (including high-expansion foam)

- Wetting agents
- Aqueous vermiculite dispersion
- Powder systems
- Oxygen reduction systems
- Portable fire extinguishers

It can be argued if these systems can be considered fire suppression systems rather than fire extinguishing systems since none of them are able to extinguish a lithium-ion battery in a thermal runway. The key role for these systems is to absorb heat and reduce the degree of propagation. As detection and early release of a suppression system is crucial to increase the effectiveness of LIB firefighting, a successful firefighting system for LIB fires combines detection and suppression methods [1, 2, 10].

In addition to water, wet and dry chemicals such as Pyrocool, F-500, FireIce, and aerosol agents have been used as suppressants. Water has been identified as the most effective agent for LIB fires [2, 3, 11]. It is determined that sprinkler protection can be effective in controlling spread if minimum separation distances of system nozzles are met [2, 3]. Water mist systems have also shown good heat absorption properties as well as the capability to reduce the gas temperature in the protected space [4]. This is an important capability since smaller ships often are built in material that is more heat sensitive (aluminum or fiber reinforced plastic) than conventional ships that are built in steel. Compared to sprinkler systems, water mist systems aim to apply considerably lower water volumes which decreases the amount of fresh water to be carried onboard.

State-of-the-art firefighting methods proposed for tackling thermal runaways in LIBs have employed water in three ways: using water mist or spray in the battery room; flooding the battery room; and flooding the battery itself [14, 15]. Applying water inside the battery room but external to the battery packs has been effective in suppressing external flames, but not in controlling propagation. Applying water inside the battery, on the other hand, has proven to mitigate the risk of propagation between battery modules and cells within the impacted module [14]. Flooding of the entire battery room with water is a technique that has not been tested.

Using water for LIB fire suppression involves several safety risks. Reactions occurring as a result of water extinguishants can conduct current and cause external short circuits in a cell resulting in thermal runaway in otherwise functioning “healthy” cells [5]. Explosion risk due to off-gas formation is a risk associated with thermal runaway as explained in the previous subsection and is understood to be of particular significance when applying water for fire suppression [14, 15]. The risk of hydrogen gas formation through electrolysis is also present when water is used as an LIB fire suppressant [5, 7].

2.5 IMO MSC/Circ.1165

The most relevant regulation for the design of an extinguishing system is IMO’s MSC/Circ.1165 [6]. This regulation sets requirements for water-based fire-extinguishing systems for use in machinery spaces of category A and cargo pump rooms. The requirements are equivalent to those for fire-extinguishing systems required by SOLAS regulation II-2/10 and chapter 5 of the Fire Safety System (FSS) Code.

Annex A sets principal requirements for the systems as well as component requirements; product consistency, specific nozzle requirements, test requirements as well as requirements to marking.

Nozzles are characterized by their flow constant K, which is the flow rate in liters per minute divided by the square root of the pressure in bars. The flow constant K is verified by water flow test as required in test requirements.

Annex B of IMO MSC/Circ.1165 describes a fire test method intended for evaluating the extinguishing effectiveness of water-based total flooding fire-extinguishing systems for protection of engine rooms of category A and cargo pump-rooms.

The test shall be performed using a test apparatus consisting of an engine mock-up and a floor plate system simulating the bilge area. The fire test shall be performed in a room having a specified area greater than 100 m2, as specified height of at least 5 m and natural ventilation through a door opening of 2 m x 2 m size.

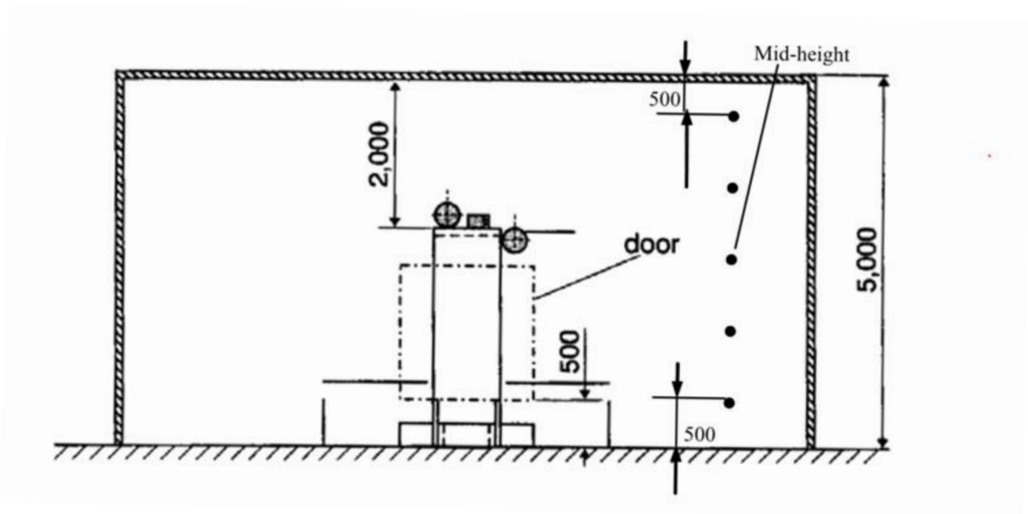

Figure 1. Test apparatus and test room

During the test, the fuel used shall be commercial fuel oil, light diesel oil, or heptane. Additionally, SAE 10W30 mineral-based lubrication oil shall be used as a test fuel for the bilge nozzles.

The classification criteria are that all fires at fire-extinguishing tests should be extinguished within 15 minutes of system activation and there should be no re-ignition or fire spread.

Classification certificates issued for prof of compliance towards IMO MSC/Circ.1165 defines the following parameters specified for the nozzles:

- Maximum horizontal spacing
- Vertical distance from object
- Minimum operation pressure
- Flow rate
- K-factor, spray heads (using Q = k x p1/2)
- Drawing number

2.6 Areas for future research

Despite being established as an effective fire suppression technique, water-based suppression systems need further investigation. The risk of off-gas toxicity, hydrogen formation, and flammability in general, are understood as an area of future research when it comes to thermal runaways [4]. The thermal behaviour of lithium-ion batteries (LIB) during firefighting has also been considered an area for future research [5].

Passive firefighting measures and issues of design such as the structure of rack enclosures, as well as the effectiveness of different thermal barriers are also recognised as areas that need to be investigated further [3]. Additionally, reducing separation distances and water demand are also identified as areas requiring further investigation [3]. These areas are important for efficient and safe fire suppression strategies in regard to a fit-for-purpose solution in smaller-sized vessels.

3 HAZID Workshop Methodology and Results

The pre-study included a Hazard Identification (HAZID) workshop to allow for exploring the safety and feasibility aspects of LIB fires in EES spaces onboard smaller marine vessels. 5 participants contributed to this workshop from 3 organisations, namely DNV, RISE, and Marioff. In order to get a clearer picture of the preventive and mitigating barriers normally implemented in EES spaces, the workshop was held after the literature study was finalized. See Appendix A.

The HAZID was carried out according to the following approach (see Figure 2), where the suppression system was considered to be installed either inside the battery casing (protective housing of battery pack) or inside the EES space (space in which the battery pack is installed). Figure 3 details the assessment process used during the HAZID.

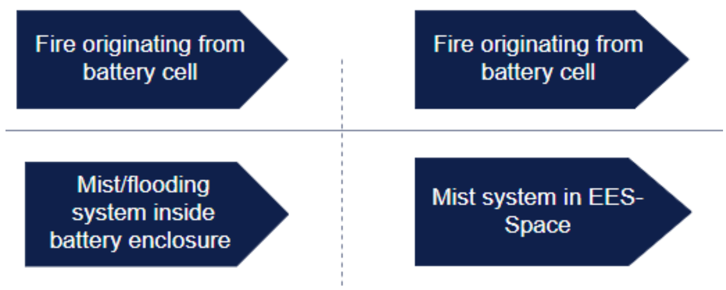

Figure 2. HAZID approach

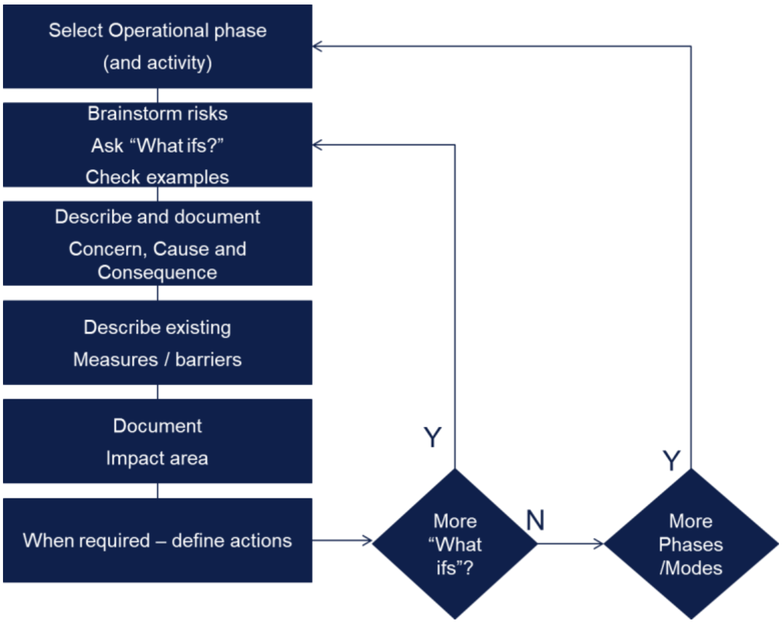

Figure 3. Assessment process

3.1 Results

The pre-study identifies several critical considerations for the development of effective fire suppression systems in small EES spaces on board ships:

1. Water mist systems installed inside the EES space will not stop thermal runaway propagation inside a battery pack as the casing is typically IP-rated.
2. Water mist systems, while effective in larger spaces, are not a viable solution for battery energy storage systems in smaller spaces. This is due to the limited volume, which can result in inadequate cooling of the atmosphere inside the space because the mist cannot spread effectively.
3. Water flooding systems may offer a better solution for fire suppression in confined spaces, with sufficient change of water, as they have proven to be effective in stopping thermal propagation. This is true especially for systems designed to flood water inside the battery pack.
4. Flooding systems connected to the battery casing will not effectively cool down the surrounding structure in case of an external fire in the EES space.
5. With current regulations, water mist systems require 30 minutes to an hour of water mist activation and may need more water compared to possible water flooding of a compartment. This makes mist systems less practical for small spaces where water supply may be limited.
6. A potential solution involves enclosing the battery in a box with an open top. This design could minimize the amount of water needed when flooding the entire battery compartment, and with relatively better cooling capacity compared to water mist systems.
7. It is noted that other liquids than water may be used to flood battery packs. These liquids typically have a boiling point that is higher than that of water. Any alternative liquid need to have similar or less environmental impact and lower electrical conductivity than water.

3.2 Functional requirements for adapted firefighting systems in small EES spaces onboard ships

The study identifies several critical considerations that must be addressed to develop functional requirements for these systems.

Water mist systems installed inside the EES space have been found ineffective in stopping fire propagation within a battery pack, especially those that are IP-rated. This limitation highlights the need for fire suppression systems that can penetrate and control or suppress fires within the battery enclosure itself. Functional requirements should include the ability to suppress internal battery fires to prevent escalation.

Furthermore, water mist systems perform inadequately in smaller EES spaces despite being effective in larger spaces. This is due to limited volume and ineffective mist spread. This shortcoming requires the development of systems specifically designed for confined spaces. Water-based firefighting systems administered inside the battery pack have been proven effective in stopping propagation. A solution based on such a system is therefore interesting to investigate. Functional requirements should ensure that these systems can operate efficiently in the limited volume of small EES spaces.

Another important consideration is cooling. Effective cooling is essential to stop thermal propagation and prevent fire re-ignition and further damage. Systems flooding water or any other agent inside the battery pack may stop thermal propagation but may not cool the surrounding structure effectively. Therefore, functional requirements may include mechanisms for both internal and external cooling to ensure comprehensive fire suppression. Especially since smaller vessels are normally built in fire and heat sensitive material.

For smaller EES spaces, water mist systems may require more water compared to flooding systems, under current regulations that require water mist activation for 30 minutes to an hour. This makes water mist systems less practical for smaller tonnage where water supply may be limited. While this limitation must be acknowledged, it cannot hinder safety of life onboard. Suppression time for water mist systems shall therefore relate to the evacuation time for the specific vessel and operation.

The study also raises the question of considering the quality of water used in fire suppression systems. Further studies on the implications of using seawater versus freshwater should advise the development of systems that can operate effectively with the available water sources on board ships. Functional requirements should specify the compatibility of systems with both seawater and freshwater.

The proposed solution of enclosing the battery pack in a box with an open top presents a potential innovation. This design could minimize the amount of water needed when flooding the entire battery space and possibly stop propagation within the battery pack. Functional requirements should not hinder the possibility to use innovative solutions such as the one described above. The size of the box would need to be determined such that the total amount of water (net volume of the box) is sufficient to provide cooling to stop thermal propagation and prevent fire re-ignition. The design of the battery pack enclosure and the sub-structure of modules and cells also need to be designed to allow water from the outside to enter and disperse to all parts.

By addressing these considerations, the study aims to develop functional requirements that ensure the safety and effectiveness of firefighting systems in small EES spaces on board ships. These requirements should guide the design and implementation of systems that can effectively manage the unique challenges posed by confined spaces and limited water supply.

3.3 Advantages and disadvantages of the new solution

The study highlights the advantages and disadvantages of traditional water mist systems used for larger machinery spaces compared to new solutions like flooding systems and innovative designs such as the open-top battery box. Traditional systems, while effective in larger spaces, face significant limitations in small EES spaces due to inadequate cooling and high water consumption. In contrast, water flooding systems and innovative solutions offer potential benefits in terms of water efficiency and effective thermal propagation control. The advantages and disadvantages of the new solution can be summarized as follows:

Advantages of the Box Solution

- Effective Propagation Control: Potential to stop fire spread within the battery pack.
- Adaptability: Better suited for confined spaces on board ships.
- Water Efficiency: Reduced water usage by containing the fire within a confined space.

Disadvantages of the Box Solution

- Structural Cooling: May not effectively cool the surrounding structure.
- Implementation Complexity: Designing and installing new solutions may require significant modifications to existing systems.

3.4 Recommendations

To ensure fire safety in small EES spaces, the study recommends the following:

1. Combining different methods, such as water mist and water flooding systems, could enhance overall effectiveness.
2. Systems may be designed to effectively supress fire using fresh water in relation to evacuation time.
3. Rigorous testing of new solutions, such as the box and battery pack enclosure design could validate their effectiveness in real-world scenarios.
4. Systems may be specifically designed to operate in the limited volume of small EES spaces.
5. The firefighting system must stop or limit thermal and fire propagation from cell to cell or from module to module.
6. Requirements on the flow rate and pressure of the suppression system shall be given.
7. The system shall provide sufficient spread of water within the confined space in case water mist systems are deployed.

It is notable that integrated systems that combine both flooding and mist solutions could provide a solution and meet the functional requirements.

3.5 Conclusions

The study underscores the importance of developing customized fire suppression systems for small electric energy storage (EES) spaces on board ships. Key findings highlight the limitations of water mist systems in confined spaces and the potential advantages of water flooding systems, particularly those designed to flood inside battery packs. The results also suggest innovative solutions, such as enclosing the battery pack in open-top boxes, to optimize water usage and potentially improve cooling effect compared to water mist fire suppression practices under current regulations.

To ensure comprehensive fire safety, integrating various suppression methods, efficient water usage, rigorous testing of new designs, and adaptability to confined spaces are recommended. By addressing these critical considerations and implementing clearer functional requirements, more fit-for-purpose standards can be developed, and the safety and reliability of firefighting systems in small EES spaces can be enhanced.

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Lighthouse gathers leading maritime stakeholders through a Triple-Helix collaboration comprising industry, society, academies and institutes to promote research, development and innovation within the maritime sector with the following vision:

Lighthouse – for a competitive, sustainable and safe maritime sector with a good working environment

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