Recommending Measures for Preventing and Responding to Lithium-ion Battery Fires at Sea

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Abstract

Our project's goal was to advise the United States Coast Guard in drafting policy and best practices for preventing and mitigating lithium-ion battery fires onboard passenger vessels and roll-on-roll-off carriers. We first reviewed existing regulations and interviewed experts in fire protection, vessel compliance, marine safety, and hazardous materials. We then documented fire prevention and protection methods. Finally, we considered the feasibility of our recommendations and the ability to enforce relevant policies. We found that prevention and early detection are the best solutions. Recommendations include policy modifications, raising awareness of safety concerns and precautions, adding specific detection and sprinkler systems, and testing the effectiveness of extinguishing agents.

Acknowledgements

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Thank you!

Executive Summary

The goal of this project was to advise the United States Coast Guard (USCG) in drafting policies and best practices for preventing and responding to lithium-ion battery (LIB) fires onboard small passenger vessels (SPVs) and roll-on-roll-off (Ro-Ro) carriers. This project seeks to identify best practices and industry standards that the USCG can adopt for personal-use LIBs, LIB installations for power or propulsion, and LIBs as cargo such as electric vehicles (EV). This study also resulted in a set of recommendations for the USCG to reduce the risks of transporting LIBs and mitigate the dangers of LIB fires if they occur.

Crew and passenger education and awareness is important in ensuring that best practices and policies are followed while SPVs are underway, as it is difficult for Marine Inspectors (MIs) to enforce personal-use LIB policies during a vessel inspection in port when there are no passengers onboard. Education and awareness may come from signage or a verbal safety brief while the vessel is departing port, similar to safety briefs in the aviation industry.

Although prevention is ideal fires will occur, and crews should be prepared and equipped to respond to them. Currently there is no standard extinguishing solution for LIBs, but fixed water mist sprinkler systems are effective in cooling the battery and absorbing smoke. Early detection systems are critical for mitigating LIB fires because they can identify the initial warning signs. Mandated firefighting training for crews currently lacks LIB-specific firefighting practices such as bouncing water under EVs to directly cool the battery.

This study was conducted through review of federal regulations, industry standards, and interviews with subject matter experts (SME) from the USCG Office of Design and Engineering Standards, Commercial Vessel Compliance Division, and Marine Safety Center; Worcester Polytechnic Institute, and the New York State Office of Fire Prevention and Control. Additional information can be found in the main report.

Background

Aside from their well-documented advantages, lithium-ion batteries (LIBs) also bring new challenges. Unexpected combustibility is one of the major safety concerns regarding the use of LIBs. LIBs supply and sustain the four necessary components of fire propagation: heat, oxygen, fuel, and a chemical chain reaction. Once LIBs ignite, they produce extreme heat and emit toxic gases, creating serious health and safety hazards.

LIB fires require responders to expend substantial time and resources when working to extinguish them. For example, a typical internal combustion engine car fire should take no more than 250 gallons of water to extinguish. An electric vehicle fire, however, may take more than 20,000 gallons. Due to this high demand for resources, a method that is currently accepted for extinguishing EV fires is allowing the fire to burn itself out while monitoring the surrounding area. While this approach to fighting LIB fires may be acceptable on the ground, this approach is not a realistic option for LIB fires on vessels since allowing a fire to engulf the ship would endanger the lives of passengers and crew.

Six major missions characterize the USCG: maritime law enforcement, maritime response, maritime prevention, marine transportation system management, maritime security operations, and defense operations. Safety practices regarding LIBs fall under the maritime prevention mission, which aims to "prevent marine casualties and property losses... by developing and enforcing federal regulations, [and] conducting safety and security inspections" (USCG, n.d., third section, "Maritime Prevention").

A significant risk for LIB fires is *thermal runaway*, which is one of the reasons these fires are so difficult to extinguish. The normal exothermic reactions within a LIB can speed up to uncontrollable levels due to damage or abuse, creating a positive feedback loop of heat release known as thermal runaway. When the amount of heat being generated within the cell is greater than the amount of heat being released from the cell, the *self-accelerating decomposition temperature* is reached, which occurs at 66.5 °C (152 °F). As the exothermic reactions continue, the cell will heat up to 75 °C (167 °F) and reach the *temperature of no return*, initiating thermal runaway. Thermal runaway can quickly propagate from one cell to the next causing the temperature of a battery to increase dramatically. Because the electrolytes used in LIBs are flammable, thermal runaway can lead to fires or explosions when their ignition temperature is reached.

When a LIB burns it releases several chemical byproducts, some of which are highly toxic and pose a significant danger to people in the vicinity of the fire. The chemistry of the components used to construct the battery cells determines which reactions take place and which products are produced during a fire. The primary gases released during LIB fires include carbon dioxide (CO_2), carbon monoxide (CO), and hydrogen fluoride (HF), which are harmful to human health and the environment.

Additional information on LIB chemistry, applications of LIBs, hazardous properties of LIBs, and their cradle to grave lifecycle can be found in the main report.

Methodology

The goal of this project was to advise the USCG in drafting policies and best practices for preventing and responding to LIB fires onboard small passenger vessels (SPVs) and roll-on-roll-off (Ro-Ro) carriers. This goal was achieved by:

1. Documenting emerging technologies and the current state of the lithium-ion battery industry.
2. Reviewing and documenting existing safety regulations regarding lithium-ion batteries.
3. Documenting existing methods of fire prevention and mitigation for lithium-ion battery fires.

4. Evaluating the financial and social feasibility of implementing proposed policies and practices.

Discussion

The above methods were used to collect data and information to support the set of recommendations. A summary of the findings are as follows:

Once a LIB fire begins, it can burn for extended periods of time. In February of 2022, the Panama-flagged Felicity Ace, a roll-on-roll-off carrier, caught fire off the coast of the Azores Islands. It is suspected that the fire was worsened by the hundreds of LIBs in the cars on board. The vessel burned for over a week before it was extinguished with the help of special equipment.

The crews onboard vessels are often the first responder to LIB fires. Unfortunately, the crews may be unprepared to fight a fire of this nature. In the case of the Ro-Ro carrier, the Höegh Xiamen, the ship was in port, yet it still took over an hour-and-a-half for the local fire department to respond, because the captain did not have the necessary contact information.

In 2019, the MV Conception in California, a dive boat, caught fire overnight and resulted in 33 casualties, the highest-casualty maritime disaster in California since 1989. The NTSB determined the cause of the fire to be the result of overcharging of personal electronic devices and determined that LIBs greatly worsened the fire.

In addition to the serious health threats of a LIB fire, there are high associated financial costs. Using the Felicity Ace as benchmark, the total economic loss caused by the fire is estimated to be between 334.6 million to 401 million US dollars from the cargo alone, not counting the cost of the vessel itself.

In the case of the Höegh Xiamen, many of the batteries in the used vehicles onboard did not have properly disconnected or secured batteries according to the appropriate standards set by the NTSB. The NTSB determined that the electrical fault that caused the fire on the Höegh Xiamen was initiated by an improperly disconnected battery.

There have been incidents of shipments of LIBs being incorrectly declared as spare computer parts to avoid hazardous material regulations. In August of 2021, a container of lithium batteries ignited on the highway while being delivered to the Port of Virginia. The batteries had been declared as computer parts, which made the response difficult for the local fire department as they encountered a more challenging fire than anticipated.

Tightly packing cargo can be dangerous, as centrally located fires will be difficult to access, making the implementation of firefighting measures difficult. In settings such as on a Ro-Ro carrier, where cars are parked as close together as possible, the inability for crews to navigate between the vehicles can make a fire inaccessible to responders. With EV fires, current sprinkler systems are inadequate because the battery is on the bottom of the vehicle.

Emerging technology in the fire prevention, detection, and suppression fields provide potential solutions that may still be a few years away from realistic implementation. Innovative battery thermal management systems (BTMS) are utilizing phase change materials for enhanced battery cooling abilities, increasing the thermal stability of batteries. Several techniques have been researched to monitor internal metrics of the battery such as temperature and voltage, but these systems are still in development and are not widely implemented. Liquid nitrogen has shown increased extinguishing abilities relative to water, but current cost and storage logistics inhibit its implementation. Novel battery chemistries are also being developed, aiming to increase the thermal stability of the battery and decrease the flammability. These chemistries currently perform worse than commonly used chemistries due to a lower energy density, inhibiting their applicability in widespread applications.

Regulations for LIBs are extensive, but there are gaps that can increase risk of a LIB incident occurring. Ferry regulations currently do not differentiate between EVs and internal combustion engine vehicles. Vague definitions for used, defective, damaged, and recycled batteries lead to their improper labelling and packaging. This makes it difficult for the USCG to enforce regulations surrounding these batteries. Differing regulations between air, maritime, and ground transportation can lead to improper packaging as batteries often utilize multiple modes during shipment, and a battery packaged to meet the requirements of one mode may not meet the requirements of another mode.

Although prevention is ideal, fires will occur, and crews should be prepared and equipped to respond to them. Early detection systems are critical for mitigating LIB fires because they can identify the initial warning signs. Mandated firefighting training for crews currently lacks LIB-specific firefighting practices such as bouncing water under EVs to directly cool the battery.

Currently there is no standard extinguishing solution for LIBs, but fixed water mist sprinkler systems are effective in cooling the battery and absorbing smoke. Water additives, such as F-500 EA, can decrease the size of water droplets, further increasing their cooling capabilities. The water additives also increase water's absorption of smoke, toxic gases, and free radicals necessary for combustion. Gaseous agents such as $C_6F_{12}O$ are effective in extinguishing a LIB fire but provide less cooling than water. Due to the LIB fire's risk of reignition, constant monitoring is necessary after a battery fire is extinguished. Solid agents such as CellBlockEx and Extover exist to contain previously extinguished or at-risk batteries until proper disposal can be arranged. These solid agents can trap toxic gases produced by the battery and absorb heat, mitigating damage caused by reignition.

Additional information regarding LIB incidents, emerging technology, existing regulations, fire prevention, and fire extinguishing methods can be found in the main report.

Recommendations

Based on our findings, we recommend the Coast Guard implement the following measures:

General Recommendations

1. Adopt the aviation industry's 30% maximum state of charge for shipped stand-alone lithium-ion batteries.
2. Educate crews on the dangers of improper charging practices.
3. Educate crews on the unique dangers of a LIB fire.
4. Require testing of used and aging batteries.
5. Require lithium-ion battery system manufacturers to provide electrolyte-specific firefighting agents.
6. Influence the drafting of NFPA code 401, Chapter 12: Battery Cells and Waste.
7. Monitor the progress and development of stable battery chemistries.

Recommendations for Small Passenger Vessels

8. Require markings and cautionary signage for appropriate charging areas.
9. Continue to follow current practices when assessing battery propulsion systems.
10. Require vessels to carry DOT-approved lithium-ion battery containers to store at-risk or previously ignited batteries.

Recommendations for Ro-Ro Carriers

11. Require a state of charge of no greater than 50% when transporting EVs.
12. Require a minimum of six feet between vehicles during transportation.
13. Increase the frequency of safety patrols in EV cargo areas.
14. Implement the use of thermal imaging devices in EV cargo areas.
15. Train crews to be prepared to fight an EV fire onboard a vessel.
16. Require water mist systems in cargo areas transporting EVs.
17. Require upward facing sprinklers on Ro-Ro decks transporting EVs.
18. Implement encapsulating agents as a water additive in fire protection systems.
19. Phase out carbon dioxide systems by implementing gaseous encapsulating agent systems.

Recommendations for the Department of Transportation

20. Refine definitions of used, recycled, damaged, defective, and recalled batteries.
21. Increase consistency across regulations of different transportation modes.

Detailed summaries of each recommendation can be found in the main report.

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Introduction	All members
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Acronym	Definition
ABS	American Bureau of Shipping
AFFF	Aqueous film forming foam
ASTM	American Society of Testing and Materials
AVD	Aqueous vermiculite dispersion
BMS	battery management system
BTMS	battery thermal management system
CFR	Code of Federal Regulations
CVC	Commercial Vessel Compliance
DOT	Department of Transportation
EAP	Emergency Action Plan
EIS	electrochemical impedance spectrum
EV	electric vehicle
FAA	Federal Aviation Administration
FFF	fluorine free foam
FTIR	Fourier transform infrared spectroscopy
GHS	Globally Harmonized System
HRR	Heat Release Rate
IMDG	International Maritime Dangerous Goods
IMO	International Maritime Organization
LCDR	Lieutenant Commander
LIB	lithium-ion battery
LIP	Lithium iron phosphate
MI	Marine Inspector
MSC	Marine Safety Center
MV	Motor Vessel
NCA	Lithium nickel cobalt aluminum oxide
NFPA	National Fire Protection Association
NMC	Lithium nickel manganese cobalt oxide
NMP	N-methyl pyrrolidone
NTSB	National Transportation Safety Board
NYS OFPC	New York State Office of Fire Prevention and Control
OSHA	Occupational Safety and Health Administration
PCC	Pure car carrier
PCM	Phase change material
PCTC	pure car and truck carrier
PHMSA	Pipeline and Hazardous Materials Safety Administration

PPE	personal protective equipment
RO-RO	Roll-on-roll-off
SBR	styrene-butadiene rubber
SCBA	self-contained breathing apparatus
SEI	solid-electrolyte interface
SME	subject matter expert
SOC	state of charge
SOH	state of health
SPV	small passenger vessel
STCW	Standards of Training, Certification, and Watchkeeping
TIC	thermal imaging camera
UL	Underwriters Laboratory
USCG	United States Coast Guard
WPI	Worcester Polytechnic Institute

1. Introduction

Lithium-ion battery (LIB) use has grown rapidly since their commercialization in 1991. LIBs have quickly become a common power source, being used in a variety of devices from smartphones to electric cars (Zubi et al., 2018). Not only are LIBs more energy dense than lead acid batteries, but they are also desirable due to their high power output capability and their ability to be recharged thousands of times with minimal degradation (Rudola et al., 2021).

Aside from their well-documented advantages, LIBs also bring new challenges. Unexpected combustibility is one of the major safety concerns regarding the use of LIBs. LIBs supply and sustain the four necessary components of fire propagation: heat, fuel, oxygen, and a chemical chain reaction (Lisbona & Snee, 2011). Once LIBs ignite, they produce extreme heat and emit toxic gases, creating serious health and safety hazards (Larsson et al., 2017).

LIB fires require responders to expend substantial time and resources when working to extinguish them. For example, a typical internal combustion engine car fire should take no more than 250 gallons of water to extinguish. An electric vehicle fire, however, may take more than 20,000 gallons. Due to this high demand for resources, a method that is currently accepted for extinguishing electric vehicle (EV) fires is allowing the fire to burn itself out while monitoring the surrounding area (V. Graves, personal communication, October 3, 2022). While this approach to fighting LIB fires may be acceptable on the ground, this approach is not a realistic option for LIB fires on vessels since allowing a fire to engulf the ship would endanger the lives of passengers and crew.

As seen in Figure 1 and Figure 5, the high heat release rate (HRR) of LIB fires, as well as their tendency to explode endangers vessels at sea (Zhang et al., 2022). With an elevated risk to life and property aboard vessels with LIBs onboard comes a greater need to establish fast acting and effective means of combatting LIB fires, as well as additional or unique safety measures to prevent these fires from occurring.

Figure 1. The roll-on-roll-off carrier Felicity Ace burns off the coast of the Azores Islands. The Felicity Ace was carrying an estimated 400 million USD worth of vehicles when a fire broke out. The ship and its cargo burned for around two weeks before sinking and becoming a total loss. *By Portuguese Navy (Marinha Portuguesa), 2022, image is in the public domain.*

The goal of this project was to advise the USCG in drafting policies and best practices for preventing and responding to LIB fires onboard small passenger vessels and roll-on-roll-off carriers. This project consisted of two parts: an executive summary and a detailed report to support the concepts discussed in the executive summary. The intended audience was Admirals and officials in the USCG. Our report was used to brief them on the dangers of LIBs and provide them with the information necessary to develop preventative policies and firefighting practices for on board LIB fires.

2. Background

In this chapter, we begin with a brief overview of the components of a LIB, practical applications of LIBs, properties that make them hazardous, and the cradle-to-grave lifecycle of a LIB, from mining to disposal. We conclude by introducing the United States Coast Guard, and their vested interest in maritime safety.

2.1 Components of a Lithium-ion Battery

As shown in Figure 3, LIBs are composed of four main components: the cathode, electrolyte, anode, and separator (Figure 3, Figure 4). These four components, when properly manufactured, keep the battery at a fixed voltage set by the battery chemistry while assisting in preventing failures that would result in a fire (Zubi et al., 2018).

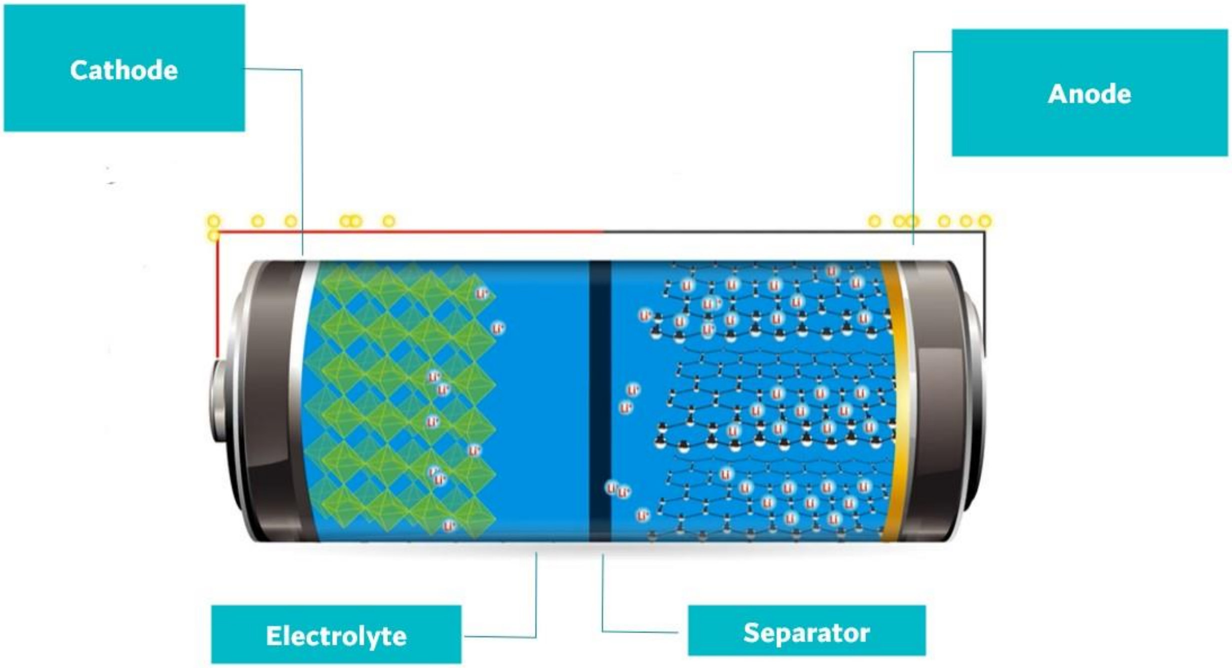


Figure 2. Diagram detailing the four main parts of a lithium-ion battery.
By Sarah Harman and Charles Joyner, 2017, image is in the public domain.

2.1.1 Cathode

The cathode is the positive electrode where electrons are removed from lithium atoms to convert them into lithium ions, which flow through the battery, when charging. The most common material for a lithium-ion cathode is lithium cobalt oxide, $LiCoO_2$ (LCO) (Li et al., 2018). This material, while adept at converting lithium atoms into ions, can ignite if its temperature passes 150 ℃ (302 °F), which is one reason it is essential to regulate the temperature of a LIB while in use or charging (Zubi et al., 2018).

2.1.2 Electrolytes

The electrolyte is a mixture of lithium salt and organic solvents which act to facilitate the transport of lithium ions (Zubi et al., 2018). This mixture is flammable and is a hazard if the temperature within the cell gets too high (Wang et al., 2005).

2.1.3 Anode

The anode is the negative electrode that donates the lithium ions through the battery to the cathode during discharge, which allows electrons to travel from the anode, through the circuit, to the cathode, while powering the device in the process. The battery becomes chemically balanced through this process and then requires charging, which is the reverse process. A graphite-based material is most common because it has a high energy density and a low first cycle capacity, so it will not absorb as many lithium ions from the cathode during initial charging, extending a battery's life and slowing its deterioration (Li et al., 2018).

2.1.5 Separator

The separator serves two functions in LIBs: preventing internal short circuiting by separating the anode from the cathode and creating a path for ionic conduction through the electrolyte (Huang, 2011). Separators are constructed of polymers that have a high electrical resistivity and a low ionic resistivity which allows LIBs to deliver a high maximum power (Huang, 2011). The separator also has a safety mechanism that will cause the path between the cathode and the anode to open if the temperature of the electrolytes becomes too high, to prevent ignition (Huang, 2011). If the separator fails due to manufacturing defects or mechanical abuse, the anode and cathode will come into contact, causing an internal short circuit. When this happens, significant heat is generated which can lead to thermal runaway (Zhao et al., 2016).

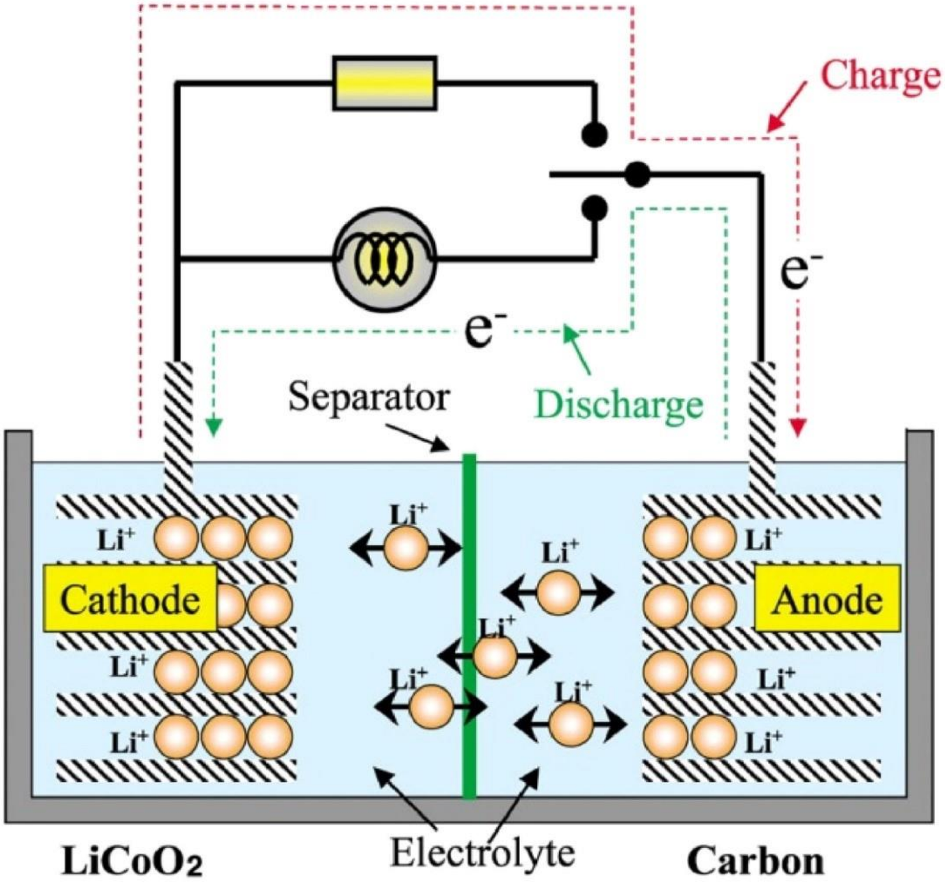


Figure 3. Inner workings of a lithium-ion battery cell, detailing the flow of electrons from the anode to the cathode then through the connected circuit back to the anode. *By Qingsong Wang, Binbin Mao, Stanislav I. Stoliarov, and Jinhua Sun, 2019, figure included with the expressed written consent of Elsevier.*

2.2 Practical Applications of Lithium-ion Batteries

2.2.1 Personal Use Lithium-ion Batteries

Personal use LIBs consist of all portable electronics such as smartphones and laptops. Over the last five years, the utilization of personal use LIBs has risen exponentially, as evidenced by the growth of the smartphone industry. In 2018, it was estimated that around 30% of people worldwide own smartphones (Zubi et al., 2018). By 2022, that number nearly tripled with an estimated 84% of people worldwide owning smartphones (*Mobile fact sheet*, 2022).

2.2.2 Lithium-ion Batteries as Marine Propulsion Systems

As LIB technology advances, LIBs are increasingly being found as the energy source for propulsion or power systems on commercial and passenger vessels. These batteries are often designed with uniquely heavier plates to survive the frequent vibrations that can occur on vessels (Verma & Kumar, 2021). Like electric cars, LIB vessel propulsion systems are desirable due to their lack of direct emissions compared to internal combustion engines. LIB propulsion systems are built with an extensive battery management system (BMS) that measures the battery's voltage, current, internal temperatures, state of charge (SOC), state of health (SOH) and calculates how long the battery can be used before it needs to be recharged. The BMS must also be capable of isolating the battery from the rest of the system if it detects a malfunction that may cause a fire. Vessel LIB systems are also supposed to undergo a complete inspection unique to the vessel while being installed to identify any hazards that a crew may encounter and try to mitigate those hazards to the best of their abilities (ASTM F 3353, 2019).

2.2.3 Lithium-ion Batteries as Vessel Cargo

LIBs may be found in cargo as individual batteries, installed in personal devices, or installed in EVs. The standards for packaging and shipping LIBs are found in Title 49 Code of Federal Regulations.

2.3 Properties of the Fire Tetrahedron

For fires to occur, four conditions must be met: the presence of heat, the presence of oxygen, the presence of fuel, and the completion of chemical chain reactions. The fire tetrahedron (Figure 4) depicts these necessary components.

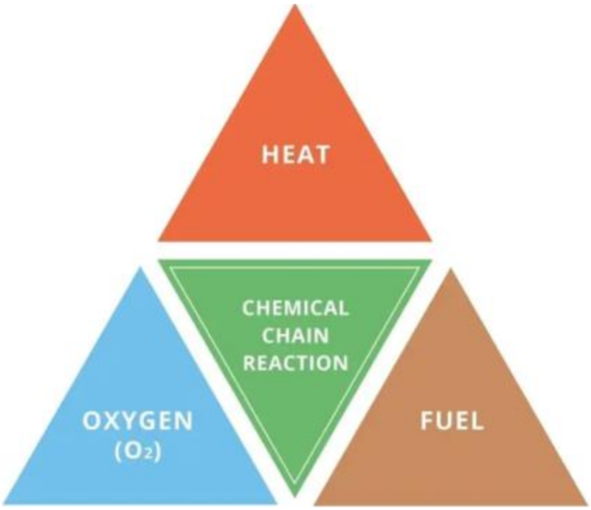


Figure 4. The fire tetrahedron depicts the four components necessary for fires to occur. Removing one of these components from a fire will extinguish it. By Hannah Spruce, 2016, image used under a Creative Commons license.

Fuel can be defined as any flammable material. In a LIB, the cathode, anode, and electrolyte are flammable. Normal exothermic reactions within a LIB produce heat and an overheated or ignited lithium-ion battery releases unstable ions known as free radicals which are used in combustion. These radicals include oxygen, which is released when the cathode decomposes, and hydrogen and methyl groups, which are flammable and explosive gases (Yuan et al., 2021).

Combustion is the chemical chain reaction necessary for fires to occur. In combustion, carbon, hydrogen, and oxygen react in the presence of heat. Because LIBs provide fuel and oxygen while also supplying heat energy through exothermic reactions, all three necessary components of combustion are present. Removing heat energy, fuel, or oxygen, or preventing them from reacting together, will extinguish a flame. This is difficult to accomplish with LIB fires, however, because the batteries themselves supply the necessary components of combustion.

2.4 Hazardous Properties of Lithium-ion Batteries

There are unique and specific hazards associated with LIB fires due to the chemistry and off-gassing of these batteries. A self-heating chemical reaction can take place within the cells, initiating a fire and causing the release of dangerous gases depending on the compounds used to construct the LIB.

2.4.1 Thermal runaway as a mechanism for lithium-ion battery fires

A significant risk for LIB fires is *thermal runaway*, which is one of the reasons these fires are so difficult to extinguish. The normal exothermic reactions within a LIB can speed up to uncontrollable levels due to damage or abuse, creating a positive feedback loop of heat release known as thermal runaway (Wang et al., 2005). When the amount of heat being generated within the cell is greater than the amount of heat being released from the cell, the *self-accelerating decomposition temperature* is reached, which occurs at 66.5 °C (152 °F) (Wang et al., 2012). As the exothermic reactions continue, the cell will heat up to 75 °C (167 °F) and reach the *temperature of no return*, initiating thermal runaway (Wang et al., 2005). Thermal runaway can quickly propagate from one cell to the next causing the temperature of a battery to increase dramatically. Because the electrolytes used in LIBs are flammable, thermal runaway can lead to fires or explosions once their ignition temperatures are reached (Wang et al., 2012).

Damage in a battery can result from mechanical, electrical, or thermal abuse (Wang et al., 2012). Mechanical abuse occurs when the cell is crushed, pierced, or otherwise physically damaged, causing internal short-circuiting to take place as the separator is unable to maintain the distance between the cathode and the anode. Electrical abuse can be caused by overcharging, over-discharging, water immersion, or other means of altering the electrochemical reactions that occur within the cell. Thermal abuse is caused by directly heating a LIB beyond its intended temperature range (Feng et al., 2020).

The SOC of a LIB directly impacts the energy of a fire. While a LIB containing more energy is not a significant hazard on its own, the extent of a fire will be greater should one occur. A LIB experiences a rise in HRR as the SOC increases (Figure 5), with a significant increase occurring once a LIB is charged beyond 30%. A higher SOC in a LIB can also be associated with a lower ignition temperature, higher maximum temperature, and faster rate of toxic gas release (He et al., 2022).

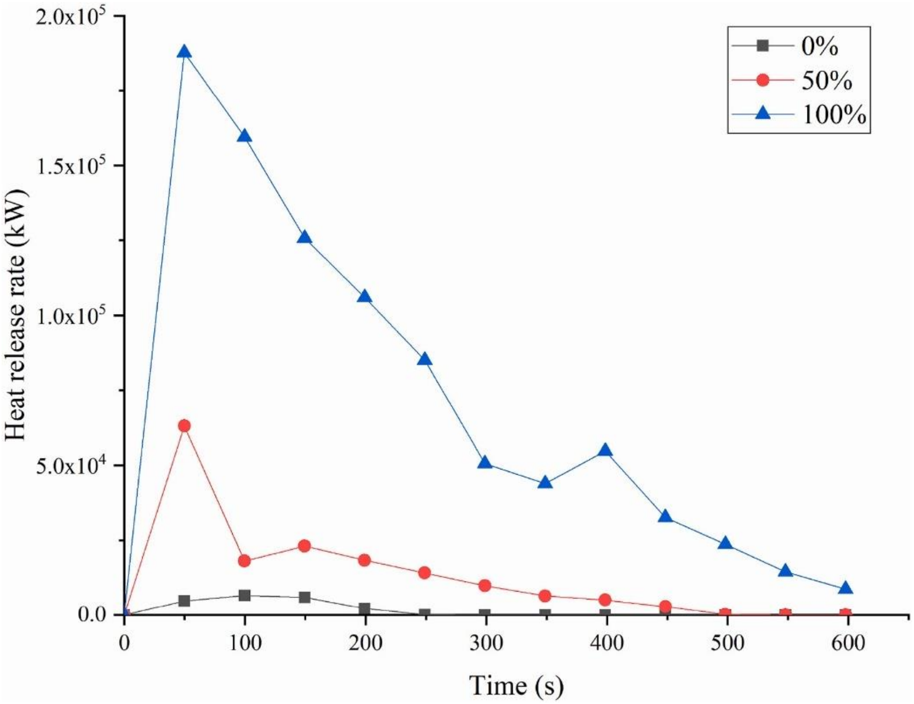


Figure 5. Chart showing the relationship between heat release rate (HRR) and state of charge. *By Jun Xie, Jiapeng Li, Jinghong Wang, Juncheng Jiang, 2022, image included with the expressed written consent of Elsevier.*

2.4.2 Hazards associated with electrolyte chemistry

Electrolytes, which are used to transfer lithium ions during charge and discharge, create a fire risk because of their flammable nature. The electrolytes in LIBs consist of lithium salts and organic solvents (Zubi et al., 2018). The most common electrolyte salt is lithium hexafluorophosphate ($LiPF_6$), but other lithium salts containing fluoride are also used (Larsson et al., 2017). The chemistry of the electrolyte determines the temperature at which the electrolyte begins to evaporate, known as its boiling point. As the electrolyte evaporates, gas accumulates in the cell and creates a buildup of pressure that can cause the battery to rupture (Wang et al., 2012). Different solvent chemistries can result in electrolyte compositions with lower boiling points and an increased probability of cell failure in the presence of high heat or during thermal runaway. (Lebedeva & Boon-Brett, 2016). Some solvents like methyl formate have boiling points as low as 32°C (90 °F), causing the electrolyte to begin evaporating at normal working condition temperatures (Lebedeva & Boon-Brett, 2016).

In addition to boiling point, solvents can be classified by characteristics such as flammability and toxicity. For example, methyl formate is classified as extremely flammable and harmful to humans, while other solvents like ethylene carbonate are only classified as an irritant

(Lebedeva & Boon-Brett, 2016). If a battery cell ruptures or is otherwise structurally compromised, boiling electrolytes will leak from the cell as a vapor. This can lead to the spread of toxic and explosive gases, creating a serious hazard for personal health and safety.

2.4.3 Harmful gases released during lithium-ion battery fires

When a LIB burns it releases several chemical byproducts, some of which are highly toxic and pose a significant danger to people in the vicinity of the fire. The chemistry of the components used to construct the battery cells determines which reactions take place and which products are produced during a fire. Different chemical compositions of the electrolyte will result in the release of different byproducts and influence the volatility of the cell (Lebedeva & Boon-Brett, 2016). For example, solvents such as 1,2-dimethoxyethane are classified as toxic according to the Globally Harmonized System (GHS) for hazard classification, and can have irreversible health effects, such as hemorrhaging of the lungs, if enough of these compounds are vaporized or released in the gaseous form (Lebedeva & Boon-Brett, 2016; Higgins et al., 1971). Volatile substances quickly enter the gas phase at elevated temperatures and become highly concentrated within the air. Furthermore, additional hazards such as fire and explosion are present if the gases are flammable. Solvents such as 2-methyl-tetrahydrofuran are toxic, volatile, and flammable, and possess significant health and safety risks (Lebedeva & Boon-Brett, 2016).

The primary gases released during LIB fires include carbon dioxide (CO_2), carbon monoxide (CO), and hydrogen fluoride (HF), which are also harmful to human health and the environment. CO is a toxic gas that acts as an asphyxiant and impacts the central nervous system (Higgins et al., 1971). HF is a highly irritating, corrosive gas which can affect heart and lung function and cause severe burns (*CDC | Facts About Hydrogen Fluoride (Hydrofluoric Acid)*, 2019). The immense amount of highly explosive, hazardous, and carcinogenic gas released by LIBs during thermal runaway poses a threat to health and safety, especially in confined space environments such as a below-deck area in a vessel (Larsson et al., 2017; Nedjalkov et al., 2016).

2.5 The Cradle-to-Grave Lifecycle of a Lithium-ion Battery

The cradle-to-grave lifecycle of a LIB consists of mining lithium ore, manufacturing cells, usage, and disposal.

2.5.1 Lithium Mining and Processing

Lithium is commercially mined from three main minerals: lepidolite, spodumene, and petalite. Around 66% of lithium mining is done through lithium brine pools, saline groundwater pools that contain solid dissolved lithium that is extracted through evaporation. As of 2021, Australia is the largest lithium producer in the world by gross tonnage, contributing a share of about 52.3%. Chile follows with 24.5%, and China contributes around 13.2%. The fastest growing lithium producers are Australia and Brazil, growing 16.8% and 16.7% respectively from 2011-2021. China is another emerging market, growing 13.0% in that timespan (*BP Statistical Review of World Energy 2022*, 2022).

When lithium ore is processed, two main compounds are created: lithium hydroxide and lithium carbonate. Lithium hydroxide is created by roasting spodumene concentrate with limestone. After roasting the lithium hydroxide with spodumene, the produced cake is then leached with hot water and calcium hydroxide. Leaching is a common mining process in which metals are extracted from ore using chemical reactions. As the solution of hot water, calcium hydroxide, and lithium ore evaporates, lithium hydroxide precipitates and is extracted. The simplicity of this technique makes it one of the most common methods used in the lithium mining industry (Yelatontsev & Mukhachev, 2021).

Lithium carbonate is created through a more complex process illustrated in Figure 6. When beta-spodumene and sulfuric acid are mixed, they undergo a chemical reaction and form a solid cake. That cake is then leached with a slurry wash to remove excess minerals. The resulting solution is filtered and then mixed with sodium carbonate so that lithium carbonate precipitates. Once the lithium carbonate precipitates it is removed through filtration, washed with hot water, and then removed again to yield the final lithium carbonate product (Yelatontsev & Mukhachev, 2021).

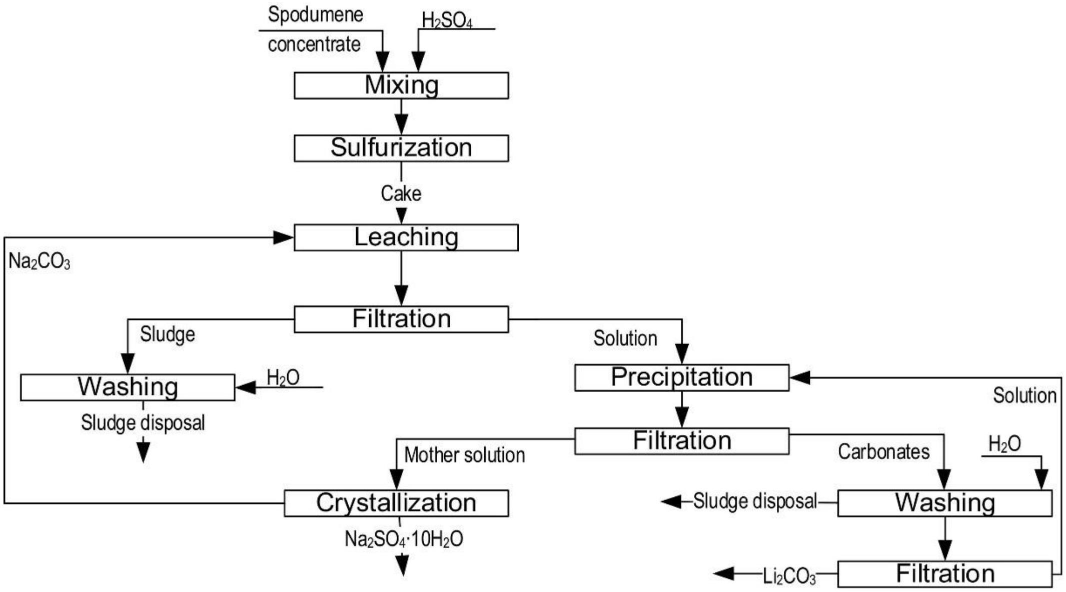


Figure 6. Flow chart of beta-spodumene processing by sulfuric acid. Spodumene concentrate and sulfuric acid are mixed, and lithium carbonate is produced at the final stage. *By Dmytro Yelatontsev and Anatoliy Mukhachev, 2021, figure included with the expressed written consent of Elsevier.*

2.5.2 Cell Manufacturing

LIB manufacturing consists of three main steps: electrode preparation, cell assembly, and battery electrochemistry activation. As of 2021, China is the world's leading LIB cell manufacturer, contributing about 79% of the global capacity and outpacing the United States – the second leading manufacturer – by a factor of 13 (*Countries' Share of Global Lithium-Ion Battery Production Capacity*, 2022).

To prepare the electrodes, a lithium compound, a conductive additive, and a binder are mixed into a slurry with a solvent. For cathodes, the most common organic solvent is N-methyl pyrrolidone (NMP). For anodes, the slurry most commonly consists of styrene-butadiene rubber (SBR), water, and carboxymethyl cellulose. The slurry is then used to coat a current collector, commonly aluminum foil for cathodes and copper foil for anodes, and then dried through a mechanical process. The electrodes are then cropped to the dimensions of the cell and sent to a vacuum oven to remove any water. After moisture is removed, the electrodes are placed in a dry room (Liu et al., 2021).

To assemble the cell, the electrodes and the separators are stacked to form the structure of the cell, and the current collectors are welded to their respective aluminum and copper tabs (Figure 7, Figure 8). The stack is then enclosed, filled with electrolyte, and sealed (Liu et al., 2021).

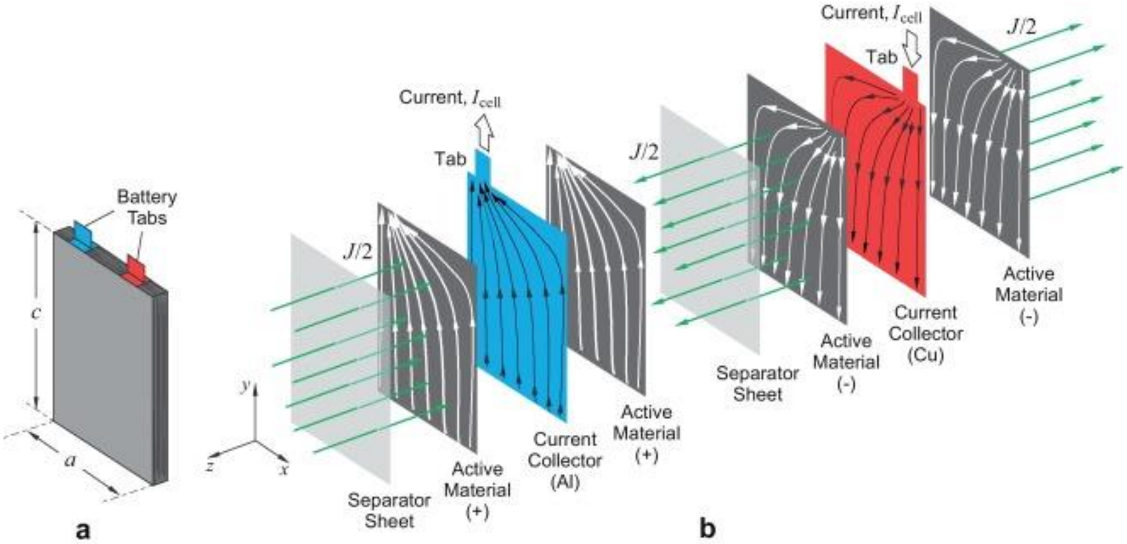
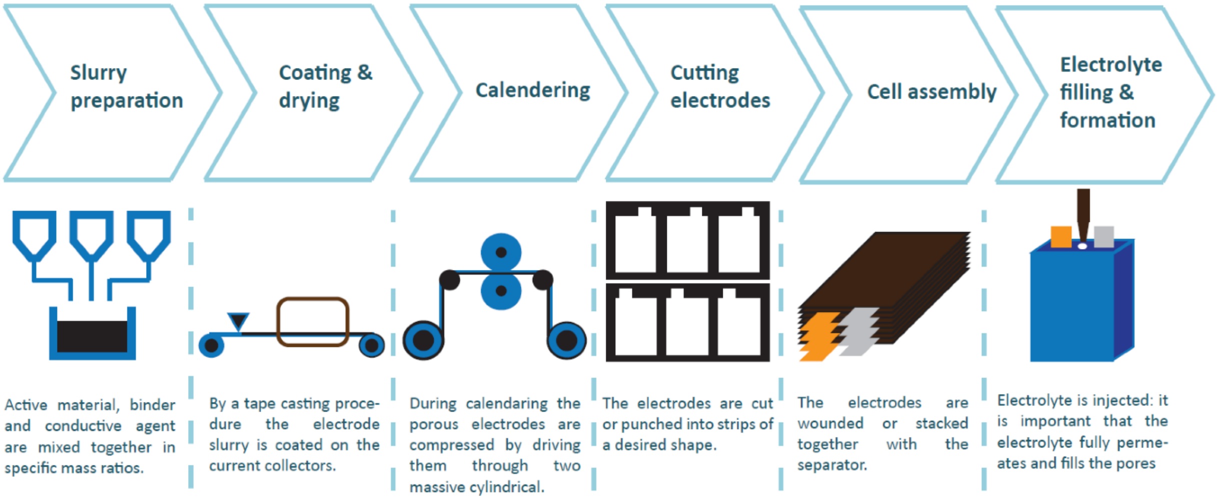


Figure 7. The active material electrodes are stacked with the current collectors and separators to form the cell. *By Peyman Taheri, Abraham Mansouri, Maryam Yazdanpour, Majid Bahrami, 2014, image included with the expressed written consent of Elsevier*.



Active material, binder and conductive agent are mixed together in specific mass ratios.

By a tape casting procedure the electrode slurry is coated on the current collectors.

During calendaring the porous electrodes are compressed by driving them through two massive cylindrical.

The electrodes are cut or punched into strips of a desired shape.

The electrodes are wounded or stacked together with the separator.

Electrolyte is injected: it is important that the electrolyte fully permeates and fills the pores

Figure 8. The battery manufacturing process. *By Jelle Smekens, Rahul Gopalakrishnan, Nils Van den Steen, Noshin Omar, Omar Hegazy, Annick Hubin and Joeri Van Mierlo, 2016, image used under CC-BY license.*

To finish the manufacturing process, a stable solid-electrolyte interface (SEI) is introduced to protect the battery from overcharging and excess consumption. The cells are then repeatedly charged at an increasing rate to stabilize the SEI. The gaseous byproducts of this process are then discharged, and the batteries are given a final seal and shipped (Liu et al., 2021).

2.5.3 Lithium-ion Batteries as Installations and Cargo on Vessels

After manufacturing and in addition to the common domestic ground-based vehicle and appliance use, LIBs are installed on vessels as an alternate power source or shipped on vessels as cargo, including inside of electric vehicles on Ro-Ro carriers. Both of these vessel applications are discussed in the Results section of this report.

2.5.4 Disposal

The global market for recycling LIBs in 2019 was 1.31 billion USD. This value is expected to rise annually, projected to reach 11.07 billion USD in 2027 (*Global Market for Li-Ion Battery Recycling*, 2021). There are three common methods for recycling LIBs: pyrometallurgy, hydrometallurgy, and direct processing. Pyrometallurgy and hydrometallurgy recover the fundamental elements in the original battery, while direct processing removes the cathode material to be used in future batteries (Ciez & Whitacre, 2019).

Pyrometallurgy consists of mixing the batteries with materials such as phosphoric acid (H_3PO_4), iron sulfate ($FeSO_4$), or lithium carbonate (Li_2CO_3), then heating them to produce a slag, where copper and nickel are recovered from the slag as an alloy. The materials remaining in the slag (Li_2O, CaO, Al_2O_3, etc.) can be used as cement inputs (Ciez & Whitacre, 2019).

Hydrometallurgy begins by separating the battery into cells and then separating cells into cathode, anode, and casing. The cathode is then soaked in warm N-methyl-2-pyrrolidone. This separates the cathode from the aluminum foil. The active material is then crushed, and calcined at 1300°F to burn off any carbon and polyvinylidene difluoride. Cobalt and lithium are then extracted using hydrogen peroxide. Graphite and copper are also recycled from the anode (Ciez & Whitacre, 2019).

Direct processing is more mechanical than the other two processes. First, the battery is discharged and disassembled into the anode, cathode, and casing. Then, the electrolyte is extracted from the active materials using CO_2 that is heated and compressed to a supercritical point, and the cell is crushed. Electrically conductive filters are then used to separate the active materials from the pulp and extract those materials for reuse (Ciez & Whitacre, 2019).

2.6 The Mission of the United States Coast Guard and its Role in Maritime Safety

Six major missions characterize the USCG: maritime law enforcement, maritime response, maritime prevention, marine transportation system management, maritime security operations, and defense operations. Safety practices regarding LIBs fall under the maritime prevention mission, which aims to “prevent marine casualties and property losses... by developing and enforcing federal regulations, [and] conducting safety and security inspections” (USCG, n.d., third section, “Maritime Prevention”).

3. Methodology

The goal of this project was to produce an executive summary-level report to advise the United States Coast Guard in drafting standards and best practices for preventing and responding to LIB fires onboard passenger vessels and roll-on-roll-off (Ro-Ro) carriers. To achieve this goal, we identified four objectives:

1. Document emerging technologies and the current state of the lithium-ion battery industry regarding manufacturing and disposal.
2. Review and document current safety regulations regarding lithium-ion batteries in the shipping and maritime industries.
3. Document the effectiveness of various methods of fire prevention and mitigation for LIB fires on passenger vessels and Ro-Ro carriers.
4. Evaluate the financial, social, and environmental feasibility of adopting new fire prevention, detection, and suppression practices.

The realization of these four objectives resulted in an executive level report with detailed appendices that was produced for presentation to the USCG. The report proposed policy changes - including shipping standards, vessel crew fire prevention and response training, and fire suppression system requirements - designed to further prevent and mitigate the impacts of LIB fires on maritime vessels.

3.1 Document Emerging Technologies and the Current State of the Lithium-ion Battery Industry

To achieve this objective, we used online databases such as Reaxys, and peer-reviewed journal articles, as well as commonly available online battery tutorials to research and document information regarding the manufacturing and disposal processes of LIBs. This research included the chemical composition of a LIB, the complete cradle to grave life cycle of an LIB, current applications of LIBs, and innovations in the LIB manufacturing and application industries. Additional research was conducted regarding the different structures of LIB cells, and the properties of LIBs that make them combustible, volatile, and toxic.

3.2 Review and Document Safety Regulations Regarding Lithium-ion Batteries

We critically assessed existing use, storage, and transportation regulations regarding LIBs on passenger vessels and Ro-Ro carriers to identify policies and regulations that are focused on preventing or mitigating LIB related fires. Through examining federal regulations governing the shipping and transportation of LIBs, an analysis of domestic fire codes, and interviews with those responsible for creating and enforcing relevant maritime policies, we developed an understanding of existing safety policies and regulations.

Federal regulations were reviewed, and key aspects documented by critically reviewing Title 46 and Title 49 of the Code of Federal Regulations from the National Archives electronic database pertaining to shipping regulations for all transportation modes, but with a focus on vessels and aircraft. International regulations as documented by the International Maritime Dangerous Goods (IMDG) Code and the United Nations were also reviewed.

Fire codes were accessed via the National Fire Protection Agency's (NFPA) online database. Relevant fire codes were compiled into a Microsoft Excel spreadsheet to illustrate the fire protection industry's current level of preparedness for a LIB incident, and critically assess how fire response may differ on a vessel at sea from a response on land.

Interviews with SMEs from the USCG's Commercial Vessel Compliance Division and Hazardous Materials Division were conducted. We followed a predetermined interview format and asked semi-structured questions regarding the USCG's current approach to LIB safety and how the Coast Guard keeps passenger vessels and cargo ships in compliance with regulations (Appendix B, Appendix C).

An interview was conducted with an officer from the USCG Marine Safety Center (MSC), and questions regarding vessel structure and structural fire protection measures were asked (Appendix E).

USCG policy letters pertaining to LIBs were reviewed and the policies set forth in the letters were documented and assessed in the previously mentioned SME interviews. These letters were accessed through the USCG CG-ENG website.

3.3 Document Methods of Fire Prevention and Mitigation

Information about existing fire extinguishing agents and their viability in particular contexts was collected through secondary analysis of research articles and reviews from various published journals. We investigated case studies and sought out commonalities which related the method of fire extinguishment used by a maritime vessel and the level of effectiveness that method had in mitigating damage from the fire.

Group interviews with SMEs in firefighting were conducted. We spoke with firefighters with experience combatting LIB fires in numerous environments with varying extinguishing agents. Three experts from the New York State Office of Fire Prevention and Control (NYS OFPC) participated in these semi-structured group interviews (Appendix D). The experts were asked to discuss their familiarity with given fire extinguishing agents and firefighting environments. The experts were then asked questions regarding firefighting training and critical skills necessary for fighting LIB fires.

An additional interview with Professor Milosh Puchovsky of Worcester Polytechnic Institute (WPI), a SME in fire protection engineering, was also semi-structured (Appendix F). Professor Puchovsky was asked to discuss risk analysis in fire protection system design and the practicality of different fire protection systems.

3.4 Evaluate the Financial and Social Feasibility of Proposed Policies and Practices

During previous interviews with SMEs from the Commercial Vessel Compliance Division (Appendix B), Hazardous Materials (Appendix C), the NYS OFPC (Appendix D), and fire protection engineering (Appendix F), the experts were asked for their assessments of existing policies and practices. Questions included where current policies fall short in the areas of packaging, small passenger vessels, firefighting training, and fire protection systems. Additional questions were asked regarding the challenges of policy enforcement and fire protection system design and implementation. The responses were then used to evaluate the feasibility of implementing the policies and practices recommended to the USCG. Considerations such as enforcement ability, financial cost, and legal authority were taken into account to finalize proposed policies.

4. Results and Findings

This section details the results of each method. The findings in this section were used to support the final recommendations.

4.1 Lessons Learned from Past Lithium-ion Battery Fire Incidents

By examining past occurrences of LIB fires, there are several lessons we can learn from commonalities in the incidents.

4.1.1 Once a lithium-ion battery fire begins, it can burn for weeks.

A characteristic of LIB fires that increases their severity is their ability to burn for extended periods of time. LIBs supply all three prerequisites necessary for the chemical reaction of combustion: heat, fuel, and oxygen (V. Graves, personal communication, October 3, 2022). This creates a self-sustaining fire, allowing batteries to burn until they have completely exhausted their fuel – the flammable components of the battery. As pictured in Figure 2, in February of 2022, the Panama-flagged Felicity Ace, a roll-on-roll-off carrier, was transporting luxury cars across the Atlantic when it caught fire off the coast of the Azores Islands. The cause of the fire is unclear; however, it is suspected that it was exacerbated by the hundreds of LIBs in the cars on board (Reuters, 2022). According to the captain of the Felicity Ace, everything five meters above the water line was ablaze (Reuters, 2022). The vessel burned for over a week before it was extinguished with the help of special equipment (“VW Fears Most of Its Cars on Burning Ship Are beyond Salvage,” 2022; Reuters, 2022).

4.1.2 Crew members onboard vessels are often unprepared and unequipped to fight lithium-ion battery fires.

Often, the crew onboard a vessel is the first responder to a LIB fire. It can take hours for professional firefighters to respond, depending on where the ship is at the time of the fire. For example, the Felicity Ace was over 200 nautical miles offshore when it caught fire (“Burnt-Out Ship Carrying Porsches and Lamborghinis Sinks in Rough Seas,” 2022). Unfortunately, the crews may be unprepared to fight a fire of this nature and can do little to extinguish or mitigate the fire while waiting for fire departments.

A commercial yacht, the Kanga, was docked off the shore of Dubrovnik in Croatia, when a fire broke out in the ship’s storage bay, believed to be caused by LIB packs (*Safety Investigation Report*, 2019). There were only nine crew members onboard at the time of the fire: the master, first officer, chief engineer, a bosun (deck crew supervisor), a deckhand, three stewardesses, and a chef (*Safety Investigation Report*, 2019). The first officer and the bosun were the designated respondents to the fire- two nonfirefighters (*Safety Investigation Report*, 2019). In less than 15 minutes--less than the time it took these two crew members to prepare to fight the fire--it had already grown out of control, spreading from the garage to the main deck, sun deck, and owner’s deck (*Safety Investigation Report*, 2019). The crew members called off the effort and elected to abandon ship. The Kanga capsized and sank, resulting in a total loss (*Safety Investigation Report*, 2019). According to the official report, the crew was unaware of the danger LIBs posed, and they were lacking the proper equipment to fight a LIB fire onboard (*Safety Investigation Report*, 2019).

In the case of the Ro-Ro carrier, the Höegh Xiamen (Figure 9), the ship was in port, yet it still took over an hour-and-a-half for the local fire department to respond (*Fire Aboard Roll-on/Roll-off Vehicle Carrier Höegh Xiamen*, 2020). The National Transportation Safety Board (NTSB) discovered in their investigation that the response was delayed because the ship's captain did not have the appropriate contact information for the local fire department and was unsure of how to report the fire to the authorities. The ship had a fixed fire extinguishing system that was designed to release carbon dioxide to suffocate the fire, but the crew did not activate the system until the fire department arrived. By then, the fire had been burning for over 90 minutes and spread to other decks (*Fire Aboard Roll-on/Roll-off Vehicle Carrier Höegh Xiamen*, 2020). The NTSB determined that this delay significantly worsened the impact of the fire (*Fire Aboard Roll-on/Roll-off Vehicle Carrier Höegh Xiamen*, 2020). It is evident that crews may be unprepared for the event of a LIB fire, which exacerbates the severity of these fires significantly.

Figure 9. Smoke coming from aft cargo deck ventilation housing exhausts on Höegh Xiamen. *By National Transportation Safety Board, 2021, image is in the public domain.*

4.1.3 Lithium-ion battery fires pose a serious risk to human health and safety and are costly for companies impacted by these fires.

LIB fires pose a serious health risk to crew members, passengers, and firefighters. In 2019, the MV Conception in California, a dive boat, caught fire overnight and resulted in 33 casualties, the highest-casualty maritime disaster in California since 1989 (Figure 11). The NTSB determined the cause of the fire to likely be electrical, believed to be the result of overcharging of personal electronic devices, and determined that LIBs greatly worsened the fire (Figure 10) (*Fire Aboard Small Passenger Vessel Conception, Platts Harbor, Channel Islands National Park, Santa Cruz Island, 21.5 Miles South-Southwest of Santa Barbara, California*, 2020).

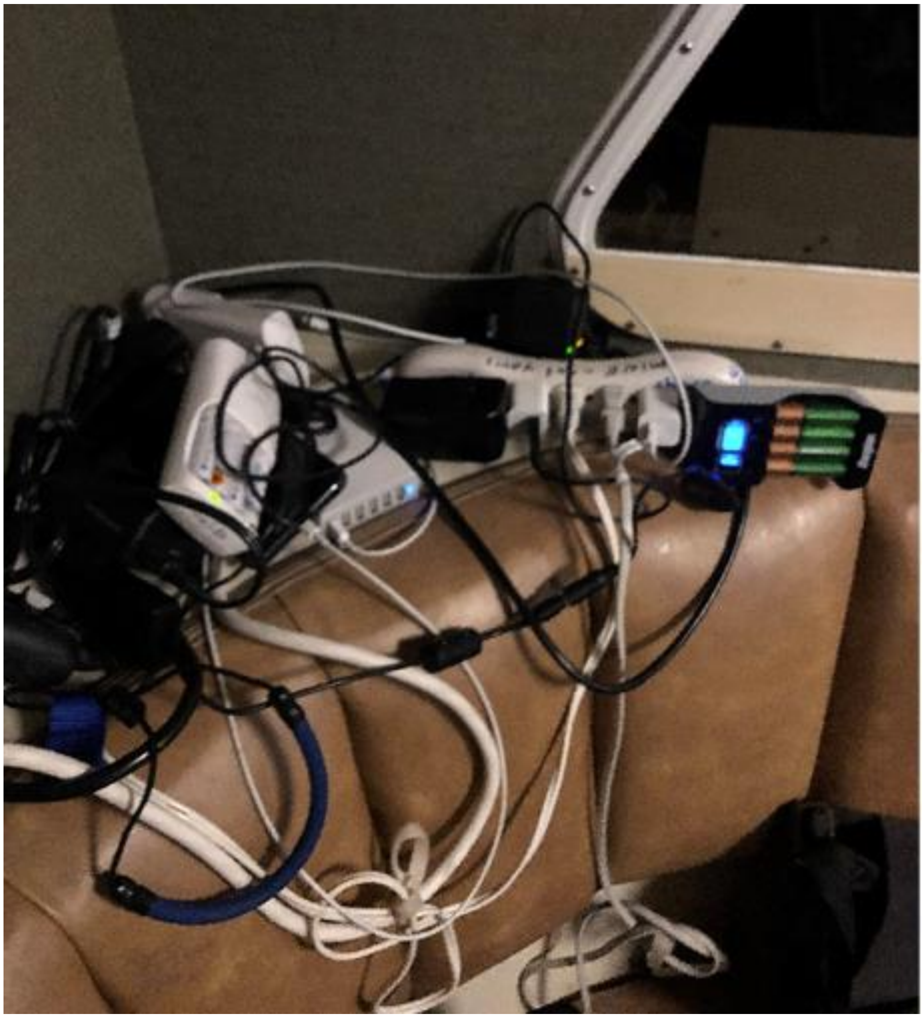


Figure 10. Photo taken during accident voyage of MV Conception showing overcharging onboard. *By J. Dignam and National Transportation Safety Board, 2019 image is in the public domain.*

Figure 11. The MV Conception prior to sinking. *By Ventura County Fire Department, 2020, image is in the public domain.*

When the Höegh Xiamen caught fire, nine firefighters were injured in an explosion onboard, with five of them being seriously injured (*Fire Aboard Roll-on/Roll-off Vehicle Carrier Höegh Xiamen*, 2020). In a non-maritime incident, UPS Airlines Flight 6 was transporting cargo between the United Arab Emirates and Germany, when a pallet of 81,000 LIBs caught fire in the cargo bay, resulting in the tragic deaths of the entire crew (*Uncontained Cargo Fire Leading to Loss of Control Inflight and Uncontrolled Descent Into Terrain*, n.d.). There are immediate dangers posed to health, and these dangers become more extreme when a fire occurs in an isolated environment, such as out on the open ocean or 30,000 feet (9144 meters) in the air. If a fire occurs far offshore, such as with the Felicity Ace, it may be difficult to abandon ship and the safety of the crew comes under immediate threat.

In addition to the serious health threats of a LIB fire, there are high associated financial costs. Using the Felicity Ace as a benchmark, the total financial loss caused by the fire is estimated to be between 334.6 million to 401 million US dollars from the cargo alone, not counting the cost of the vessel itself (“VW Fears Most of Its Cars on Burning Ship Are Beyond Salvage,” 2022). The vessel was transporting approximately 1,100 Porsches and 189 Bentleys, along with around 2,800 other luxury vehicles (Reuters, 2022). The Kanga is another example of serious financial loss, with the capsizing and sinking of the 40.8-meter-long luxury yacht (*Safety Investigation Report*, 2019). The costs of LIB fires can be extremely high given their severity, and there is a large financial incentive for stronger shipping and fire mitigation regulations.

4.1.4 Ignorance of safety regulations increases the risk of fires occurring.

Although fires can still break out when regulations are followed, improper following of safety regulations increases the risk of fire. In the case of the Höegh Xiamen, many of the batteries in the used vehicles onboard did not have properly disconnected or secured batteries according to the appropriate standards set by the NTSB (*Fire Aboard Roll-on/Roll-off Vehicle Carrier Höegh Xiamen*, 2020). The NTSB determined that the electrical fault that caused the fire on the Höegh Xiamen was initiated by an improperly disconnected battery and determined that the crew had several instances where they could have caught this mistake but missed the opportunity (*Fire Aboard Roll-on/Roll-off Vehicle Carrier Höegh Xiamen*, 2020).

There have also been incidents of shipments of LIBs being incorrectly declared as spare computer parts to avoid hazardous material regulations. In August of 2021, a container of lithium batteries ignited on the highway while being delivered to the Port of Virginia. The batteries had been declared as computer parts, which made the response difficult for the local fire department as they encountered a more challenging fire than anticipated (*Marine Safety Alert: Lithium Battery Fire*, 2022). This also happened on the Cosco Pacific, a container ship, in January of 2020. A container of lithium batteries was declared as spare parts and improperly packaged. The improper packaging was unable to contain the fire, and the ship's crew was unprepared to address a LIB fire onboard (Savvides, 2020).

4.1.5 Tightly packing cargo greatly increases the risk of a fire spreading.

Corporations and shipping companies seek to fit as much cargo on a ship as possible to maximize the economic efficiency of each trip (Figure 12). Tightly packing cargo can be dangerous, however, as centrally located fires will be difficult to access, making the implementation of firefighting measures difficult (Figure 13). In settings such as on a Ro-Ro carrier, where cars are parked as close together as possible, the inability for crews to navigate between the vehicles can make a fire inaccessible to responders. With EV fires, which are difficult to extinguish with current sprinkler systems due to the batteries being shielded by the body of the car, human intervention may be crucial in stopping their spread.

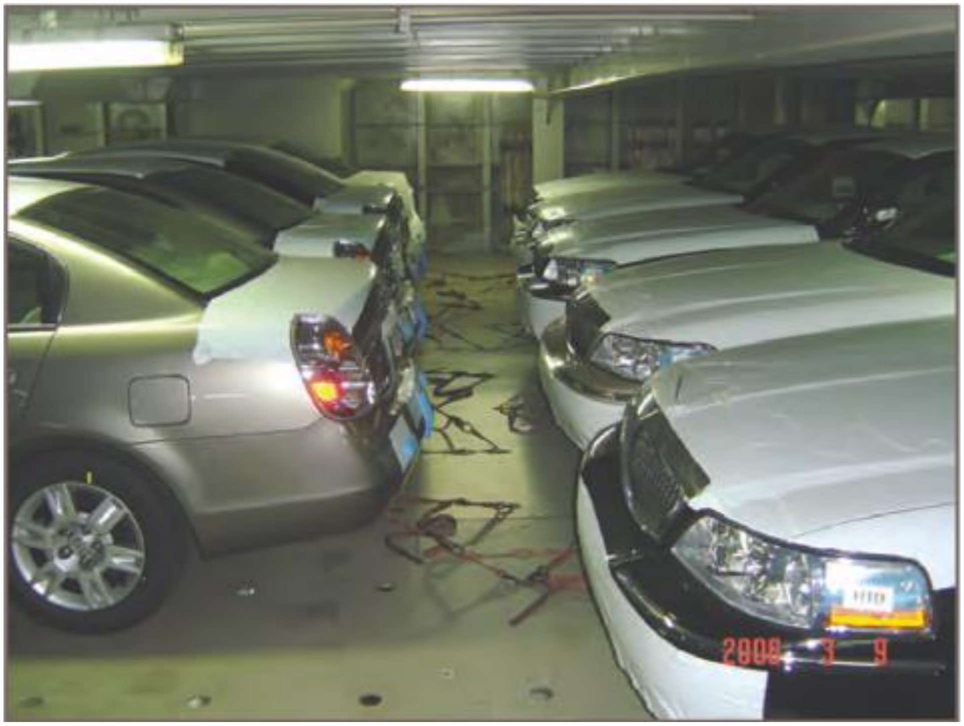


Figure 12. Cars loaded on a ro-ro deck. *By the Occupational Safety and Health Administration, 2006, image is in the public domain.*

Figure 13. Burnt vehicles on the vessel Honor, showing the close packing of the cars. *By the National Transportation Safety Board, 2017, image is in the public domain.*

A simulated experiment by Tohir and Spearpoint analyzed the risk of a car fire spreading to adjacent vehicles in a parking garage can be related to Ro-Ro carriers, where cars are parked as tightly together as possible. The simulation found that, in a typical parking space ranging from 2.2 to 3.2 meters (7.2 to 10.5 feet) wide where two adjacent vehicles are parked in the center of their respective parking space, a fire has up to a 0.90 probability of spreading to the adjacent vehicle if no extinguishing efforts are made (Figure 15). When an additional parking space was left vacant between two vehicles in the experiment, the maximum probability of fire spread was 0.23 and a probability of 0.00 was able to be attained (Figure 16) (Tohir & Spearpoint, 2019). Figure 14 depicts the measurement of the effective distance, a plus 2b, used in the experiment.

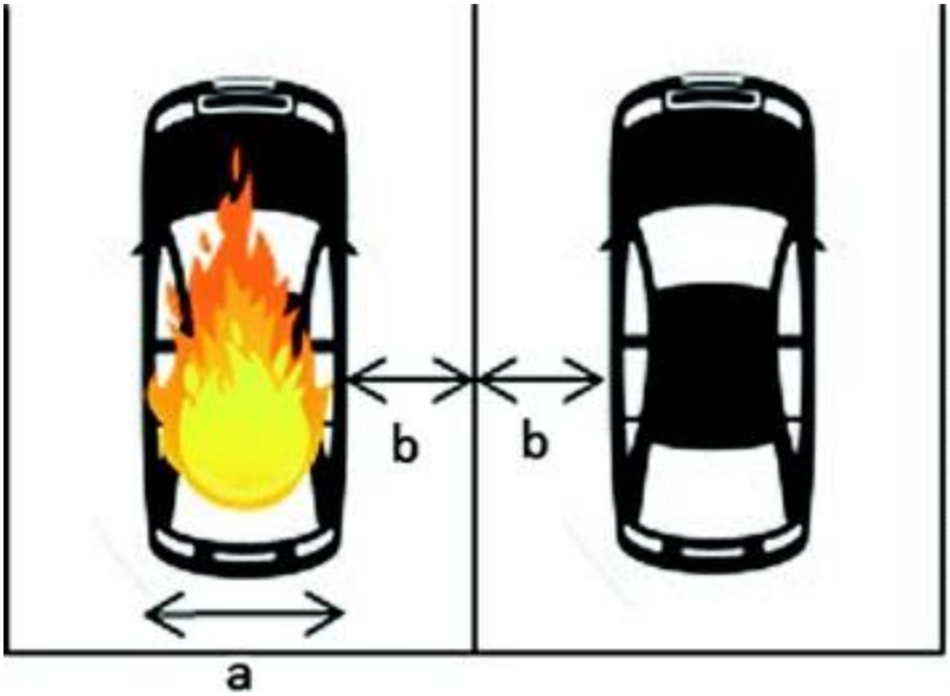


Figure 14 The effective distance used in the simulations by Tohir and Spearpoint was measured as a plus 2b, which ranged from 2.2 – 3.2 meters (7.2 to 10.5 feet) when the vehicles were in adjacent spaces, and 4.4 – 6.4 meters (14.4 – 21.0 feet) when there was a vacant space between two vehicles. *By Mohd Zahirasri Mohd Tohir and Michael Spearpoint, 2019, image included with express written consent of Springer Nature.*

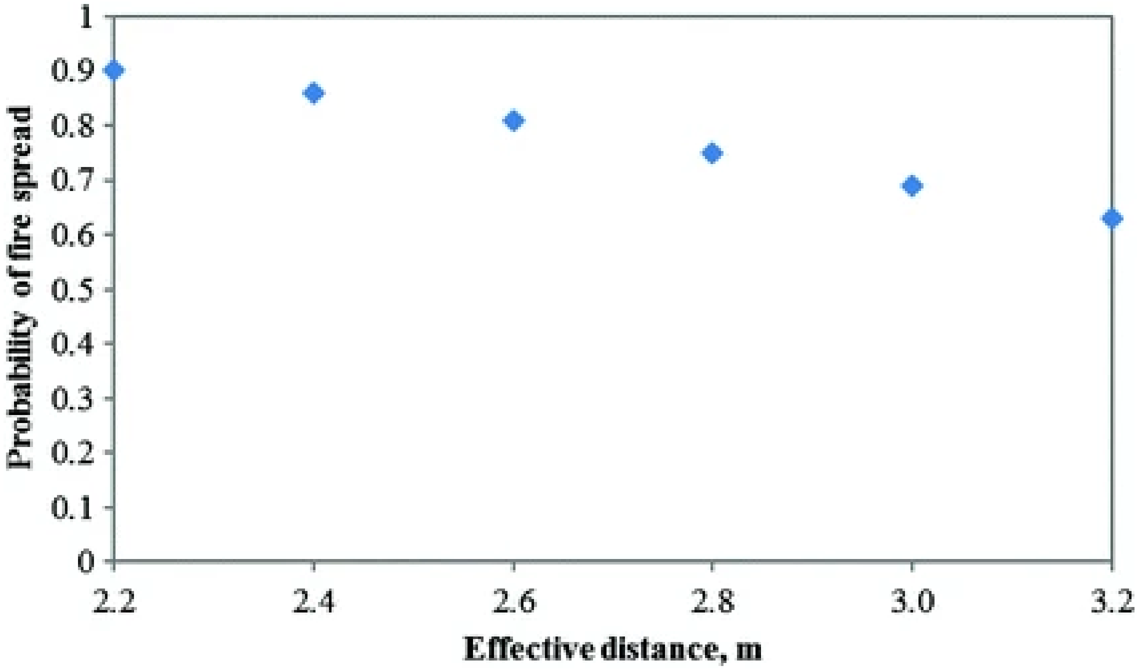


Figure 15 A probability of fire spread vs effective distance plot, showing that as the effective distance between vehicles increases, the probability of fire spread between adjacently parked vehicles decreases. *By Mohd Zahirasri Mohd Tohir and Michael Spearpoint, 2019, image included with express written consent of Springer Nature.*

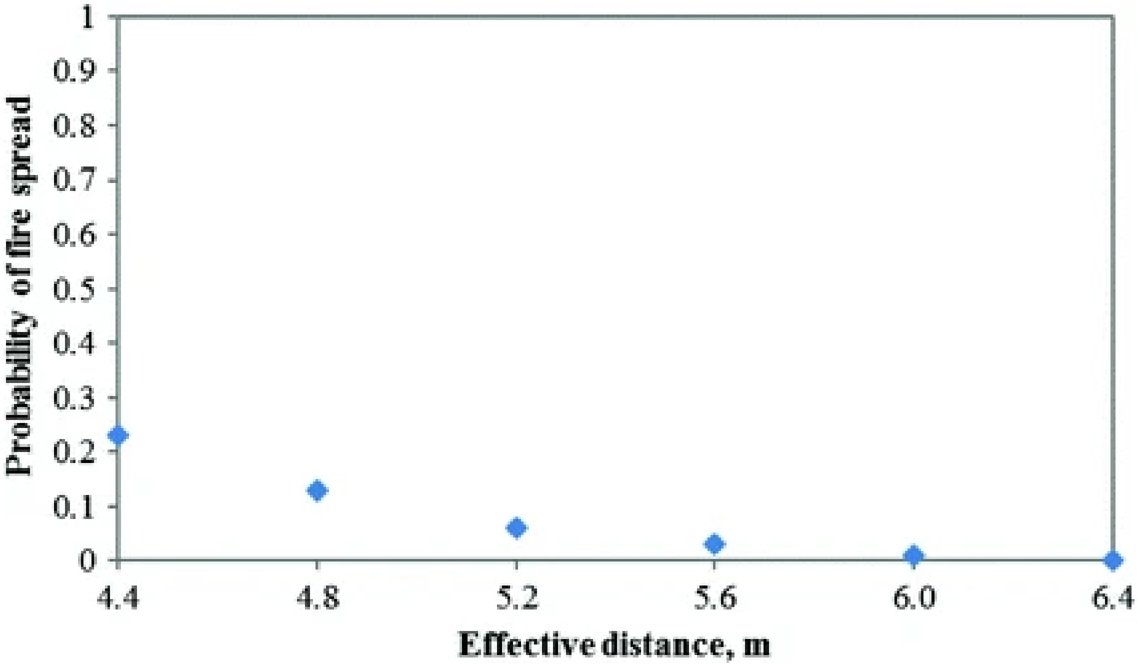


Figure 16 A probability of fire spread vs effective distance plot, showing that as the effective distance between vehicles increases, the probability of fire spread between the vehicles decreases. *By Mohd Zahirasri Mohd Tohir and Michael Spearpoint, 2019, image included with express written consent of Springer Nature.*

Parking spaces allow for people to walk between parked cars, but cars on a Ro-Ro ship are parked only inches apart from each other. From this information, coupled with the higher

HRR associated with EVs than other automobiles, it can be inferred that EV fires on a Ro-Ro have more than a 0.90 probability of spreading to adjacent vehicles if firefighting intervention cannot be made (Tohir & Spearpoint, 2019).

4.2 Emerging Technology and the Current State of the Lithium-ion Battery Industry

4.2.1 Battery Thermal Management Systems

A battery thermal management system (BTMS) is a term for a device responsible for monitoring, regulating, and dissipating the heat generated by a battery cell. One innovative form of BTMS is based on phase change materials (PCM). PCMs are substances that release or absorb a great amount of heat during their phase change to provide cooling or heating. If PCMs can be integrated into a LIB, they would be able to absorb the heat generated by the battery during use to prevent the battery from entering thermal runaway (Luo et al., 2021).

PCMs that show potential for use in a BTMS can be categorized as organic and inorganic. Organic PCMs are better studied and are desirable for their low cost, high stability, and low toxicity. However, further research is required in the use of organic PCMs due to issues of flammability and low thermal conductivity. There is currently work being done to integrate both conductive and flame-retardant substances into organic PCMs to mitigate these risks. Inorganic materials, commonly composed of hydrated salts, have undergone less research than organic materials but have shown potential. Inorganic PCMs are nonflammable and are less costly than organic PCMs. Unfortunately, inorganic PCMs have a low thermal conductivity and they possess unstable thermophysical properties, resulting in the inconsistent absorption of heat energy from the LIB. Current experimentation to increase the thermal conductivity in a PCM is being performed by adding highly conductive metals, such as graphene, to metal-based materials and carbon-based materials (Luo et al., 2021).

4.2.2 Extinguishing Agents

Liquid nitrogen (Figure 17) has been used in a wide variety of fields such as the medical and industrial field as a rapid coolant. It has also shown potential for use as an extinguishing agent for LIB fires but has not been applied in the commercial world yet. In experiments performed, liquid nitrogen has been shown to be effective as small droplets evaporate upon contact with the surface of the battery to form a vapor film. The film evaporates and nitrogen’s thermal resistance causes heat transfer from the LIB to occur, cooling the battery in the process. While liquid nitrogen cannot stop thermal runaway once it starts, it can effectively delay thermal runaway by lowering the surface temperature of the battery to about –100 ^{o}C (-148 ^{o}F), however, the temperature of the battery continues to rise when liquid nitrogen is no longer applied due to the exothermic reactions that persist within the battery (Huang et al., 2021).

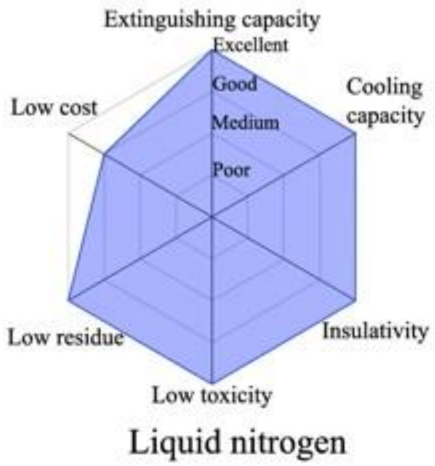


Figure 17. Radar plot of the performance of liquid nitrogen as a firefighting agent. Extinguishing capacity defines an agent's general ability to extinguish LIB fires and Cooling capacity defines an agent's ability to remove heat from a LIB. Insulativity defines an agent's lack of electric conductivity and Low toxicity defines the agent's environmental and human health impacts. Low residue defines the cleanup required after an agent's use and Low cost defines the financial cost necessary to implement and utilize the agent. *By Shuai Yuan, Chongye Chang, Shuaishuai Yan, Pan Zhou, Xinming Qian, Mengqi Yuan, Kai Liu, 2021, figure included with the express written consent of Elsevier.*

4.2.3 Fire Detection Methods

The internal temperature of the core of a LIB can be hundreds of degrees Celsius higher than the surface, so a noticeable drop in the difference between the two would be a sign that thermal runaway is imminent. A method to consistently monitor this temperature difference is comprised of inserting a flexible thin film thermocouple, a wired device used to measure temperature, within the pouch cells of the battery to constantly measure the internal temperature of it. Another thermocouple would then be placed on the surface of the battery so the differences in temperature can be constantly compared (Sun et al., 2021). Although this method has been proven effective in a static laboratory setting and shows potential, it has yet to be tested in practical, more versatile settings. It has also only been tested with batteries while in use so it is difficult to know how well it would work on a deactivated battery as cargo.

Another indicator that thermal runaway will occur is a drop in voltage. It is typical that as the voltage of a system decreases, the temperature increases as observed by Sun et al., that there was a sharp voltage decrease in a LIB right before thermal runaway occurred. Thus, constantly monitoring the voltage of a LIB would also be a clear indicator of a sharp increase in temperature, which indicated thermal runaway will occur. Another factor that can be considered for detection is the electrochemical impedance spectrum (EIS). It is possible to measure the phase shift between the applied sinusoidal current and resultant voltage of a LIB using a phase meter. This is important because this phase shift is directly dependent on the internal temperature of the LIB so measuring it would give an effective way to constantly monitor the internal temperature (Sun et al., 2021).

As a LIB heats up and approaches thermal runaway, it will also begin releasing gases that can be detected. Most gases that are released are specific to the kind of LIB since each manufacturer implements a unique chemical makeup which may not be open to the public. However, it is almost certain that a LIB entering thermal runaway will at least release CO, HF and CH_4. Both gases can already be measured using certain gas detectors but depending on how far the detectors are from the LIB, it may not be able to detect gases before thermal runaway occurs. If placed directly in the casing of a battery, a gas detector could detect these gases up to 10 minutes before thermal runaway occurs. However, this is not a viable consideration for the shippers and vessel operators and would have to be implemented by the manufacturer when making their product. For this reason, there is a proposed method of gas detection that will couple gas chromatography with Fourier transform infrared spectroscopy (FTIR) and mass spectrometry. This technique can constantly monitor which gases are released by a LIB before and during thermal runaway using gas chromatography and FTIR, while mass spectrometry precisely identifies the mass percentage of each gas that is released. This experiment has also only been tested with an overcharged LIB and has not been tested on a maritime vessel so further testing is required to determine the effectiveness of this method (Sun et al., 2021).

4.2.4 Safe Packaging Methods

A way to keep LIBs at an appropriate temperature during packaging is the patented Mark Petzinger Battery Cooling Method. This method intends to keep a battery at a low temperature and absorb heat produced during thermal runaway. It consists of a plastic pouch containing water mixed with sodium polyacrylate that would be placed both on top of and under a package of LIBs. Another method specifically for EVs is a thin sodium alginate film with a 99% water content. This film would be placed on the surface of an EV's battery pack to constantly cool the battery. It also contains a water automatic-refilling system that would constantly refresh its own water content by absorbing water vapor (Quintiere, 2020). Another experiment was conducted in which the typical cardboard packaging that individual LIBs are packaged in was replaced with packaging made of a sponge material. This method, which is meant for a battery that has already entered thermal runaway, begins supplying the sponge with a constant supply of boiling water when a battery enters thermal runaway to keep its temperature from increasing past 100^{o}C (212 ^{o}F). Boiling water has a high heat transfer coefficient and can significantly reduce the temperature of a battery in thermal runaway more effectively than cold water. In addition, the flow rate of a sponge allows it to supply water constantly from the sponge reservoir (Quintiere, 2022).

4.2.5 Lithium Iron Phosphate Batteries

Different cathode compositions create different flammability properties. Lithium iron phosphate (LIP) cathodes ($LiFePO_4$) are more thermally stable than other common cathodes, making them a safer option than other common cathodes such as lithium nickel manganese cobalt oxide (NMC) and lithium nickel cobalt aluminum oxide (NCA). A drawback of LIP cathodes is their low specific energy which causes worse performance when compared to NMC and NCA cathodes. This worse performance hinders their applications in EVs (Zubi et al., 2018). Increasing LIP cathodes' performance is an emerging field of research, and if the performance could come close to the level of an NCA or NMC cathode, LIP cathodes could emerge as a safe and stable chemistry for most applications, decreasing the risk of fire.

4.3 Existing Regulations Surrounding the Shipping of Lithium-ion Batteries

4.3.1 Title 46, Code of Federal Regulations, Shipping

A review of federal regulations reflected a generic code for fire prevention and response. Title 46 of the United States Code of Federal Regulations (CFR) presents regulations surrounding shipping. In Chapter 1, the regulations pertaining to the USCG are documented. Subchapter I discusses regulations surrounding cargo and miscellaneous vessels, including ventilation, fire detection, and fire protection systems in areas designed for storing vehicles. In accordance with 46 CFR Part 92, subpart 92.15, all areas transporting vehicles that are below the weather deck must maintain constant ventilation (*46 CFR Part 92 Subpart 92.15 -- Ventilation*, n.d.). Part 95, subpart 95.05 states that all enclosed spaces designed for transporting vehicles must have a fire detection and alarm system (*46 CFR Part 95 Subpart 95.05 -- Fire Detection and Extinguishing Equipment*, n.d.). Additionally, federal regulations state that all spaces designed for vehicles must possess a carbon dioxide fixed-fire extinguishing system (*46 CFR Part 95 Subpart 95.15 -- Carbon Dioxide Extinguishing Systems, Details*, n.d.). A non-vehicle space-specific regulation states that in fixed clean agent gas extinguishing systems installed on cargo vessels, clean agents must "address and minimize risks of combustion products and decomposition byproducts." Clean agents include halocarbons and inert gases (*46 CFR Part 95 Subpart 95.16 -- Fixed Clean Agent Gas Extinguishing Systems, Details*, n.d.).

In passenger vessels over 100 gross tons, vessels with sleeping accommodations for more than 150 passengers, and all vessels on international voyages, there exist structural regulations to be followed in the construction of the vessel. All hulls, bulkheads, decks, and deckhouses must be constructed of steel, and any rugs or carpets in corridors and stairways must be wool or an "equivalent fire-resistive material" (*46 CFR Part 72 Subpart 72.05 -- Structural Fire Protection*, n.d.). Any self-propelled vessel with sleeping accommodations for more than six people must be equipped with fire pumps, hydrants, hoses, and nozzles. All manual sprinklers must have the capacity to apply 12 gallons of water for every 100 square feet of deck space (*46 CFR Part 76 -- Fire Protection Equipment*, n.d.).

4.3.2 Title 49, Code of Federal Regulations, Transportation

Title 49 of the CFR contains regulations surrounding the transportation of hazardous materials, including LIBs. There is a 9-class classification system, with LIBs being considered a Class 9, miscellaneous hazardous material. There are four main United Nations classifications for LIBs: UN3480, UN3481 UN3171, UN3536. General lithium-ion batteries shipped by themselves are classified as UN3480 materials (*49 CFR 172.101 -- Purpose and Use of Hazardous Materials Table.*, n.d.). 49 CFR Part 173 subpart 173.185 outlines packaging requirements for UN3480 LIBs, stating that cells and batteries must be packaged in a way to prevent short-circuiting, prevent shifting, and separated from conductive material (*49 CFR 173.185 -- Lithium Cells and Batteries.*, n.d.). UN3481 materials are LIBs packed with or contained in other equipment. For these objects, the equipment must be packed such that accidental activation is avoided and shifting is prevented. UN3171 materials are battery-powered vehicles and are subject to specific shipping requirements. During shipping, the battery must be secured in the battery holder and protected to avoid short-circuits. This involves the use of nonconductive caps on the battery terminal to prevent accidental contact with conductive material (*49 CFR 173.220 -- Internal Combustion Engines, Vehicles, Machinery Containing Internal Combustion Engines, Battery-Powered Equipment or Machinery, Fuel Cell-Powered Equipment or Machinery.*, n.d.). When being stowed, the batteries must be inspected for leakage, damage, and electrical faults prior to being loaded onto the vessel (*49 CFR 176.905 -- Stowage of Vehicles.*, n.d.).

When shipping damaged batteries, there are stricter regulations for packaging. The requirements for packaging damaged LIBs are outlined in 49 CFR 173.185. The cell or battery must be completely enclosed in a non-metallic inner package that is surrounded by a non-combustible, non-conductive, absorbent cushioning material. The package must be marked to denote a damaged battery for proper identification. Damaged LIBs can only be transported by rail, road, or vessel; they are forbidden from being transported by air (*49 CFR 173.185 -- Lithium Cells and Batteries.*, n.d.). Stricter regulations for damaged batteries reflect the enhanced danger of shipping damaged LIBs.

The Department of Transportation (DOT) requires that all employees involved in the shipment of hazardous materials must complete training covering general awareness, function-specific training, safety, and security awareness (*49 CFR 172.704 -- Training Requirements.*, n.d.). The DOT allows employers to construct their own training programs so long as they cover the topics outlined. General awareness topics include packaging, markings, and shipping papers. Safety training may include topics such as emergency response, fire prevention plans, PPE, and fixed extinguishing systems (*Guide to Developing a Hazmat Training Program: General Awareness, Function-Specific, Safety, Security Awareness, and In-Depth Security Training.*, 2018). In accordance with 49 CFR part 176, subpart 176.13, a carrier cannot transport hazardous materials unless all crewmembers involved are trained to the DOT standards, and these vessels must always keep records of this training onboard (*49 CFR 176.13 -- Responsibility for Compliance and Training.*, n.d.).

Vehicle transportation by ferry (Figure 18) is governed by 49 CFR Part 176.90 and 49 CFR Part 176.905. Part 176.905 states that batteries must be inspected prior to loading and protected from damage and short circuiting. Vehicles are exempt from these regulations when stored in an area approved for transporting vehicles (*49 CFR 176.905 -- Stowage of Vehicles.*, n.d.).

Figure 18. Cars stowed on a ferry deck. *By Erika Lentz, Woods Hole Coastal and Marine Science Center, U.S. Geological Survey, 2019, image is in the public domain.*

4.3.3 Interviews with Subject Matter Experts

The interview with Lieutenant Commander Shawn Karasevicz of the USCG Marine Safety Center (MSC) was conducted virtually. This interview focused on structural regulations present in vessel design and construction aimed at preventing and mitigating LIB fires. LCDR Karasevicz stated that the USCG uses policy letters as "interim ways of saying what's acceptable" when federal legislation lags behind industry. He said that vessels should have a ventilation system that would vent gases from thermal runaway overboard, away from passengers and crews. LCDR Karasevicz believes that US regulations are more strict than international regulations, specifically in fixed fire protection systems, as the US requires a fixed water-based system, whereas many international associations permit a fixed clean-agent system instead. Most LIB plan proposals that the MSC reviews involve updating existing ships to fit them with LIB systems, which leads to concerns over the preparedness of the vessel to protect against a LIB fire. Since most of the existing vessels the MSC reviews are not built for LIB systems, they often lack the structural protection that a specially designed vessel would have.

The interview with Dr. Amy Parker, the lead chemical engineer of the Bulk Solids and Packaged Hazmat team in the Hazardous Materials Division of the Office of Design and Engineering Standards (CG-ENG-5), occurred virtually. This interview focused on regulations surrounding the transportation and packaging of LIBs. Dr. Parker stated that current definitions of used, defective, and damaged batteries are vague, and there is room to refine them. More descriptive definitions can help shippers properly identify LIB shipments and minimize the potential for accidental improper packaging. Dr. Parker identified the lack of regulations surrounding used and recycled LIBs as an area of concern to the USCG. Another area for improvement is “broader harmony across the transportation regulations per mode,” reducing the variation in regulations for trucks and rails, vessels, and aircraft. She stated that there are no regulations in spacing vehicles onboard a Ro-Ro carrier, and companies will try to put as many vehicles on one shipment as possible.

4.3.4 International Regulations

The United States also follows the regulations set forth by the International Maritime Dangerous Goods Code (IMDG). These regulations state that any lithium battery or cell needs a venting device, must be equipped to prevent external short circuiting, and must be able to prevent reverse current flow if connected in parallel (*International Maritime Goods Code*, 2020, p. 94).

4.3.5 United States Coast Guard Policy Letters

The USCG publishes policy letters that provide interim guidance until they can pass proper legislation. In 2019, the USCG Office of Design and Engineering Standards (CG-ENG) published a policy letter titled Design Guidance for Lithium-ion Battery Installations Onboard Commercial Vessels. This letter outlines some guidance for the design and implementation of LIB power systems on commercial vessels to adhere to existing regulations. The letter states that the USCG requires qualitative failure analysis, design verification test procedures, and periodic safety test procedures to be included in design plans submitted to the USCG for approval. The letter also states that the document Standard Guide for Shipboard Use of Lithium-ion Batteries, published by the American Society for Testing and Materials (ASTM), provides a sufficient level of safety in the areas of testing requirements, operating environment, fire safety, battery system design and testing and maintenance (Compher, 2019).

In 2020, the USCG published an additional policy letter titled Carriage of Lithium-Ion Batteries on Small Passenger Vessels. It contains guidance for marine inspectors (MIs) inspecting small passenger vessels, which fall under 46 CFR, Subchapters K and T. While the previous policy letter focused on LIB systems installed on vessels, this letter focuses on personal use LIBs. The letter contains standards for storing, charging, and using LIBs on these vessels. It states that LIBs should be stored in “a dry and cool location away from combustible material.” It also states that charging should be supervised, either through a person watching or a smoke detector. Charging should also not be conducted through connected power strips, each charger should have a single outlet, and the device should be disconnected once it is fully charged. Finally, the letter states that a device should be powered by batteries made by the device’s manufacturer or an authorized reseller, and damaged batteries should be removed and placed in a fire-resistant container (Edwards, 2020).

4.3.6 Industry Standards

The American Bureau of Shipping (ABS) assists USCG in setting forth best practices for transporting EVs on Ro-Ro carriers with regards to vehicle stowage, charging, fire detection, crew training, and firefighting. Through workshops with representatives from stakeholders such as car manufacturers, regulatory bodies, and vessel operators, ABS conducted surveys to determine these best practices. For vehicle stowage, 66% of ferry experts said that segregating vehicles on ferries was impractical and unnecessary, however, 66% of pure car carriers (PCC) and pure car and truck carrier (PCTC) experts said that segregating vehicles was appropriate on PCCs and PCTCs. If the vehicle is damaged, most experts agree with segregating the damaged vehicles, with dissenters believing they should not be loaded onto a vessel at all. On ferries, 100% of the experts surveyed believed that EVs should only be charged from outlets that are specifically designed for EV charging and can be disconnected from the shipboard power source in the event of a fire. On PCCs and PCTCs, this number drops to 83%, with the other 17% stating that EVs should not be charged on board at all. When asked about the use of video monitoring systems as a method of fire detection, 100% of ferry experts and 67% of PCC and PCTC experts agreed that it was an appropriate practice. The concern with a video monitoring system is that the ceiling height of the decks might minimize the view and make it ineffective. 67% of ferry experts and 84% of PCC and PCTC experts believed that increasing fire patrol frequency in areas with EVs would help fire detection and be an appropriate practice. Crew fatigue was a major concern with this practice. 100% of ferry experts and 89% of PCC and PCTC experts stated that using thermal imaging cameras (TICs) would be a helpful practice for early detection. A unanimous consensus was that crew members should be able to recognize an EV, understand the risk of high voltage equipment, and be aware of the toxic off gases of a LIB. 67% of ferry experts and 53% of PCC and PCTC experts stated that fixed water mist and deluge systems in areas with EVs would be an effective best practice, with concerns surrounding the effectiveness of water as a fire extinguishing agent (*Best Practices for the Transport of Electric Vehicles On Board Vessels*, 2022).

The Standard Guide for Shipboard Use of Lithium-ion Batteries, or ASTM F3353-19, is a document published by the American Society for Testing and Materials that sets forth standards for LIB systems on vessels. It requires that LIBs be tested in accordance with UL 1642 standards, and that LIB systems be tested to IEC 62619 standards. It also requires the installation to be propagation adverse, such that if one battery fails, that failure will not spread to adjacent batteries. The standard states that the space the battery is installed should be kept at an ambient temperature within the operating range of the battery, and that means of monitoring both the temperature and the concentration of flammable and toxic off gases should be present in the battery space. In fire safety, the ASTM requires fire integrity ratings of A-60 towards any machinery spaces, passenger areas, and fuel tanks, with all other areas possessing an A-0 integrity rating. They also state that fixed fire and smoke detection, gas detection, and internal temperature sensors should be installed in the battery space. The fire extinguishing system should be water mist or spray or an equivalent cooling agent. LIB systems are required to have a battery management system (BMS) that is either designed by the battery manufacturer or certified by both manufacturers as being compatible. The BMS must be able to monitor and communicate battery voltage, battery current, battery internal temperatures, battery balance ground faults, SOC, and SOH. The BMS must be designed to be able to isolate a battery in the case of failure. The battery system should undergo a safety assessment to identify risks to passengers and crew and develop an appropriate training system to mitigate risk. A qualitative failure analysis, design verification tests, and periodic safety test procedures should also be conducted on LIB systems installed on vessels (*Standard Guide for Shipboard Use of Lithium-Ion Batteries*, 2019).

4.3.7 Battery Testing Standards

Manufactured LIBs are designed to meet extensive battery testing standards. Independent laboratories, such as Underwriters Laboratories (UL), test manufactured batteries and apply their seal of certification upon successfully meeting the test criteria. A UL certified battery is guaranteed to meet commercial, federal, and international regulations governing product safety during typical use and when damaged or improperly used to an extent. UL tests batteries by abusing them in a multitude of ways and determining if the level of abuse before failure was acceptable. The figures below show a list of tests performed on LIBs intended for personal use such as within devices, at both the cell (Table 1) and battery (Table 2) level. For detailed descriptions of the tests, see UL 2054. Table 3 shows similar tests performed on EV batteries, and more details on the tests can be found at UL 2580. It is important to note that testing is performed on new batteries that have not been used and are younger than six months old. Used and aged batteries are not currently tested unless they are going to be removed and reused in a different capacity than previously intended.

UL Standard 2054 Table 8.1

Testing required for cells

Test	Number of Cells Tested
Electrical Tests	
Short Circuit	
at room temp	5
at 55 °C (131 ° F)	5
Abnormal Charging	5
Forced-Discharge	5
Mechanical Tests	
Crush	5
Impact	5
Shock	5
Vibration	5
Fire Exposure Tests	
Projectile	5
Environmental Tests	
Heating	5
Temperature Cycling	5

Table 1. A table of the various tests performed by Underwriters Laboratories on battery cells. Each test is performed on 5 cells. *Table was reproduced with express written consent from Underwriters Laboratories.*

UL Standard 2054 Table 8.2

Testing required for battery packs

Test	Number of fully charged packs
Electrical Tests	
Short Circuit	
at room temp	5 (unsealed)
at 55 °C (131 ° F)	5 (unsealed)
Abnormal Charging	5 (unsealed)
Forced-Discharge	5 (unsealed)
Forced-Discharge*	5 (unsealed)
Limited Power Source	6 (unsealed)
Battery Pack Component Temperature	2 (unsealed)
Battery Pack Surface Temperature	2 (complete)
Battery Enclosure Tests	
Steady Force	3 (complete)
Mold Stress Relief	3 (complete)
Drop Impact	3 (complete)
Enclosure Flammability**	3 (+3, if necessary) unsealed enclosures

Table 2. A table of the various tests performed by Underwriters Laboratories on battery packs. Each test is performed on 5 cells. Unsealed refers to batteries which do not use securement such as adhesive and/or ultrasonic welding to seal the top and bottom enclosures to facilitate access to the inside of the battery pack. Complete refers to a whole sample of the battery pack representative of production.

* Forced-Discharge* test is conducted only for multi-cell series configurations.

** Enclosure materials classified as V-1 or less flammable in the minimum part thickness do not require enclosure flammability.

Table was reproduced with express written consent from Underwriters Laboratories.

UL Standard 2580 Table 18.1
Tests and sample requirements for electric energy storage assemblies (EESA) and component electric energy storage assemblies

Test	Number of EESA samples
Electrical Tests	
Overcharge	1
Short Circuit	1
Overdischarge Protection	1
Temperature	1
Imbalanced Charging	1
Dielectric Voltage Withstand	(Use Temperature Sample)
Isolation Resistance	(Use Temperature Sample)
Continuity	(Use Temperature Sample)
Failure of Cooling/Thermal Stability System	1
Mechanical Tests	
Rotation	1
Vibration Endurance	1
Shock	1
Drop	1
Crush	1
Environmental Tests	
Thermal Cycling	1
Salt Spray	1
Immersion	1
External Fire Exposure	1
Single Cell Failure Design Tolerance	1
Materials Tests	
20-mm End Product Flame Test (not conducted if minimum V-1)	3 test specimens of the part under test (polymeric enclosure sample)

Table 3. A table of the various tests performed by Underwriters Laboratories on electric energy storage assemblies (EESAs). The sample used in the temperature sample in the electrical tests is also used as the dielectric voltage withstand sample, isolation resistance sample, and the continuity sample.
Table was reproduced with express written consent from Underwriters Laboratories.

4.3.8 Fire Codes

The NFPA sets codes for preventing and responding to fires that are recognized and accepted throughout the world. Since LIBs are categorized as Class 9, miscellaneous hazardous materials, the NFPA requires that employees working where hazardous materials are stored and handled are trained to recognize the hazards associated with the materials and the actions that must be taken if an incident occurs. The training must be completed before working and should include familiarity with the Emergency Action Plan (EAP) employed, how to read and locate safety data sheets, and knowledge of the specific hazards associated with the materials (NFPA 400, 2022 Edition). The NFPA also assigns distinct levels of responsibility to those responding to hazardous materials incidents. Awareness level personnel are those who may encounter a hazardous materials incident while completing their normal duties. Individuals at this level must be able to identify hazardous materials, the containers that store hazardous materials, and what the markings on the containers indicate. Operations level personnel are more knowledgeable about the chemical structure of the hazardous materials, are aware of the required measures for the transportation of the materials and are given mission specific responsibilities for hazardous materials incidents (NFPA 400, 2022 Edition). The development of a structure detailing the responsibilities of those involved in the incident facilitates a faster response and can be critical when responding to situations regarding hazardous materials.

The NFPA advises that vessels should be self-sufficient when controlling fires, extinguishing fires, and preventing the loss of life and property due to fire. Vessel owners should not rely on outside entities such as port fire departments for extinguishing fires (NFPA 301, 2023 Edition). However, if a fire takes place in a marina or boatyard, the fire department in the area should be notified quickly. The crew should still be aware of the location of the firefighting equipment in the boatyard and fire drills should be conducted at least twice per year. The firefighting equipment must be inspected and maintained according to the guidance provided by the manufacturer (NFPA 303, 2021 Edition). For vessels utilized for pleasure and motor craft, the NFPA lists the location, number, and types of fire extinguishers onboard depending on the size and gross tonnage of the vessel. This code also advises the use of clean agent firefighting systems to put out fires in machinery spaces depending on the volume of the compartment. The possible firefighting agents include carbon dioxide, halogenated agents, and HFC-227ea (NFPA 302, 2020 Edition).

Fixed carbon dioxide systems are permitted for use in the design of new cargo holds and find use in applications where utilizing systems with extinguishing agents such as water would damage the cargo. Total flooding carbon dioxide systems can be used in normally occupied spaces on vessels if discharge alarms, a time delayed release, and emergency lockout valves are incorporated into the design (NFPA 12, 2022 Edition). Since it is critical to attempt to extinguish LIB fires as quickly as possible when the fire is still in the incipient stage, a time delayed release may cause the fire to grow and spread to nearby cargo. For spaces greater than 6000 ft^3, automatic carbon dioxide systems are not viable as it could be difficult to escape the area before carbon dioxide is discharged. According to NFPA 12, carbon dioxide systems in areas that are normally occupied must have a time delay of at least 20 seconds after the discharge alarm sounds. The time delay is critical for crew and passenger safety as carbon dioxide can lead to dizziness, fainting, and even death. The NFPA advises that the concentration of carbon dioxide in machinery spaces should be at least 34% of the total air concentration, creating an environment lethal to humans. At this concentration "loss of controlled and purposeful activity, unconsciousness, convulsions, coma, and death" can occur in less than a minute (NFPA 12, 2022 Edition). Entrances and exits must be gastight to prevent carbon dioxide from diffusing to areas of the vessel. NFPA 12 mentions the amount of carbon dioxide necessary for vehicles powered by liquid fuels, requiring different gas release rates used to achieve the 34% concentration for vehicles with greater than or less than five gallons of fuel. There is no mention of the amount of carbon dioxide that should be discharged in areas containing EVs, however, let alone the time constraint, the 34% design concentration must be met within. The NFPA also emphasizes that carbon dioxide systems can be used for most applications except for materials containing oxygen and active metals (NFPA 12, 2022 Edition). LIBs fall into this category as the lithium-metal oxide cathode contains oxygen, making carbon dioxide systems ineffective for suppressing LIB fires.

A challenge with LIB fires is that when a LIB burns, many harmful gases are released. Over time, the gases may accumulate in a compartment, causing a lethal and potentially explosive environment. To reduce the likelihood of an explosion, the gases expelled from the burning LIB can be removed through a ventilation system. For flammable gas mixtures, the ventilation system should be designed using the component of the mixture with the highest fundamental burning velocity, which is the rate at which a flame spreads through a mixture containing unburned fuel (NFPA 68, 2018 Edition). Two ways to lessen the risk of deflagration fires and explosions are by reducing the amount of oxygen in the compartment or by reducing the amount of fuel in the compartment. Since LIBs do not require external oxygen to burn, a lower concentration of oxygen in the air is unlikely to stop the fire. Reducing the concentration of fuel involves venting the flammable gases from the compartment so that the concentration of the gaseous mixture does not reach its lower flammable limit. When designing a ventilation system, the plans should include information about the chemical and physical characteristics of the materials being vented, the location of the material, the limits of the hazards, and areas with exposure to the vented material (NFPA 69, 2019 Edition). For many LIB systems, the chemical composition of the battery is proprietary knowledge, therefore, it is difficult to determine the most effective ventilation system to prevent LIB fires and explosions.

For the transportation of LIBs, the area containing the batteries should not be greater than 900 ft^2 and should be separated by other areas containing LIBs by a distance of at least 10 ft. The area where the LIB containers are located should have a smoke detection system and an automatic sprinkler system. If there is the potential for explosion or fire from the offgassing of the LIB, a plan to minimize this risk should be approved by the authority having jurisdiction. The NFPA also outlines the procedure to follow if a LIB fire takes place starting with donning PPE and a self-contained breathing apparatus. The responders should isolate and shutdown the system, confine the area of the incident, and then work to suppress the fire and vent the dangerous gases (NFPA 855, 2023 Edition). The choice of suppressant for the energy storage system depends on the chemistry of the material being burned as some firefighting agents are more efficient for certain battery chemistries. The NFPA suggests that water is still the best option for extinguishing LIB fires due to its abundance and cooling capacity. Foams should not be used for LIB fires due to their conductive and insulative properties and low cooling ability which can increase the rate of thermal runaway. Carbon dioxide and dry powders are also ineffective at extinguishing LIB fires due to a low cooling capacity. These systems may extinguish the initial flames but do little to reduce the internal temperature of the LIB (NFPA 855, 2023 Edition).

The NFPA is currently drafting a new edition of NFPA 401 for preventing fires and chemical reactions during the handling of hazardous waste. This code will include information about practices for shipping lithium-ion batteries, labeling containers carrying LIBs, and the suggested training for those responding to LIB fires (NFPA 401). However, currently there is no official NFPA code that addresses the best practices for preventing and responding to LIB fires during shipping.

4.3.9 Regulations in Other Industries

The rules for shipping lithium-ion batteries are governed by the regulations in Title 49 but vary in strictness between land, maritime, and air transportation. Land travel, which has the least strict regulations of the three modes, adheres to general requirements upon which maritime and air regulations are built upon. When motor vehicles transport LIBs to recycling or disposal facilities, they can be granted exemptions from packaging regulations. (*49 CFR 173.185 -- Lithium Cells and Batteries., n.d.*).

The regulations for shipping LIBs by air include a majority of the regulations for land and sea, along with additional air-specific requirements. The most notable air-specific regulation is the complete prohibition of transporting damaged LIBs. On aircraft, the SOC of a standalone LIB must be no higher than 30% throughout the entire journey. Packages containing small, standalone LIBs must not exceed a weight of 2.5 kg (5.5 lbs.) per package. The overall quantity of batteries shipped by air is also limited, whereas no limits for land and maritime shipments exist (*49 CFR 175 – Carriage by Aircraft*).

Title 49 states that if an individual or company participates in paid transportation of passengers, the passengers must be made aware by the company of any hazardous material that may be onboard during the duration of the flight before the purchase of a ticket if possible and must continue to be notified throughout each major stage of the boarding process, such as receiving a boarding pass and checking their luggage. It is also stated that if a company is receiving cargo containing LIB that they will clearly inform the person giving the cargo of the rules and regulations for which a LIB must be packaged under, which are outlined under Title 49. Any errors in the packaging of a LIB must be brought to the attention of the nearest Federal Aviation Administration (FAA) regional office prior to the departure of the flight. In addition, when a LIB is shipped as cargo on an aircraft, the operator of the aircraft must provide shipping papers providing essential information related to the flight and hazardous material, such as the date of the flight, the proper shipping name of the material and the proper identification number of the material. It must also include a signed confirmation from the pilot-in-command that there was no evidence of any damage to the LIB prior to the departure of the vessel (*49 CFR 175 – Carriage by Aircraft*).

4.4 Fire Prevention and Firefighting Measures

The unpredictability and instability of LIBs only increases the dangers associated with LIB combustion. A major deciding factor in the approach taken to combat a fire is the environment in which fuel is burning. Extinguishing agents and the method of their application will vary not only from ship to ship, but from room to room on a ship. In this section, firefighting practices will be described as *conventional*, or traditional methods, and *novel*, or new and innovative methods. Extinguishing agents are categorized by their state of matter— solid, liquid, or gas — during application.

4.4.1 Fire Response Training

Crew members are the first responders to onboard fires, so proper education and preparedness is important for firefighting and fire mitigation. Currently, the USCG mandates a basic training course for all Merchant Mariners, the United States force of civilian mariners, in 46 CFR 11.302. The training curriculum comes from the Standards of Training, Certification and Watchkeeping (STCW) and can be offered either by the company hiring the crew member, or by a USCG-certified third-party. The training includes SCBA use, portable fire extinguisher operation, using water, foams, and powders to extinguish small and extensive fires, and firefighting in smoke-filled areas (*46 CFR 11.302 -- Basic Training.*, n.d.). Officers responsible for the fire response on a commercial vessel must complete advanced firefighting as well, outlined in 46 CFR 11.303. This training includes controlling firefighting operations through communication, organization, ventilation control, fire precautions based on specific materials and fire detection and extinguishing system inspection and servicing. For both trainings, recertification must occur every five years to stay licensed (*46 CFR 11.303 -- Advanced Firefighting.*, n.d.).

Crews onboard SPVs under Subchapter T of 46 CFR are not subject to the same training requirements as the Merchant Mariners. Crews on T boats must be trained in the use of firefighting equipment, location of equipment, egress routes, fire and smoke detection systems, and classification of fire. This training must occur when a crew member is first hired, and at least once every three months after (*46 CFR 185.420 -- Crew Training.*, n.d.).

The virtual interview with representatives of the NYS OFPC included State Fire Chief Ben Keller and fire protection specialists Deputy Chief Victor Graves and Teresa Baker. This interview focused primarily on the basic firefighter training that would be necessary to effectively extinguish a LIB fire. Teresa Baker identified that the fire services do not currently have a set standard for fighting LIB fires, and Deputy Chief Graves noted that current training plans are still only in the ideation stage and are mostly comprised of LIB identification and education. All three experts emphasized that properly donning PPE is the most important action that can be taken in a fire, especially in a LIB fire, because the individuals responding to the scene need to protect themselves first. Deputy Chief Victor Graves could not stress enough that full turnout gear including gloves and an SCBA should always be worn in all environments when engaging with a LIB fire. Another topic emphasized by Teresa Baker was the concept of “perishable skills” and the need to regularly train to maintain the knowledge and ability necessary to fight a fire. Chief Ben Keller suggested that crew members trained to fight fires on ships may liken to fire brigades employed commercially by large warehouses and factories. He also noted, however, that the OSHA code 1910.156 governing the training of those brigades is, in his opinion, lacking.

4.4.2 Fire Detection

Throughout the interviews, a point that was repeated several times was the importance of early detection for mitigating LIB fires. The two main ways of fire detection include fixed automatic fire detection systems, and manned patrols. Current regulations require a fire detection and alarm system in areas “specially suitable for vehicles” on cargo vessels, such as ro-ro decks (*46 CFR Part 95 Subpart 95.05 -- Fire Detection and Extinguishing Equipment*, n.d.). On passenger vessels under Subchapter H of 46 CFR, which includes vessels making international voyages, vessels longer than 150 feet (46 meters) with sleeping accommodations, or a vessel with sleeping accommodations for more than 50 people, a fire detection system is required. Ro-ro carriers will often fall into the second category. These fire detection systems can be disabled on ro-ro decks during loading and unloading but must be reactivated immediately after. While these detectors are off, the area must be occupied by a crew member (*46 CFR 76.27-10 -- Operation.*, n.d.). Detectors on H vessels “must be responsive to heat, smoke, or other products of combustion, flame, or any combination of these factors” (*46 CFR 76.27-15 -- Detectors.*, n.d.).

The ABS published a document titled Guide for Enhanced Fire Protection Arrangements in July of 2022, in which they outline some recommendations for fire detection systems for vessels with ro-ro areas. They state that in addition to the regulations outlined previously, the decks should also have a CCTV monitoring station that is always manned (*Guide for Enhanced Fire Protection Arrangements*, 2022). In another ABS document, Marine Vessel Rules, they state that ro-ro spaces designed for EVs should also have a minimum of two thermal-imaging devices stored with the firefighting outfits (*Rules for Building and Classing Marine Vessels*, 2022). In the ABS workshop previously mentioned, the majority of experts were in favor of video monitoring system use in areas designated for EVs (*Best Practices for the Transport of Electric Vehicles On Board Vessels*, 2022).

Manned patrol systems are another method of fire detection. In the ABS workshop, the majority of experts agreed that increasing crew patrols in areas with EVs was a good practice for early detection. They also agreed that supplying these patrols with thermal-imaging devices was a good practice. On H boats, a supervised patrol must be present between 2200 and 0600 in all parts of the ship except machine rooms and occupied sleeping quarters (*46 CFR Part 78 Subpart 78.30 -- Lookouts, Pilothouse Watch, Patrolmen, and Watchmen,* n.d.).

One issue that arose in the interview with Professor Puchovsky is the effect of battery chemistry on the offgas byproducts. When the battery enters thermal runaway and gases are produced, the specific type of gas depends on the chemistry of the electrolyte. This chemistry is proprietary knowledge of the manufacturer, and therefore it is difficult to build a sensor to detect the correct gases. There are common offgases such as carbon monoxide and hydrogen fluoride, but the specific gases released are impossible to know.

Passive fire detection systems lessen the burden on safety patrols and allow for constant monitoring of areas. Systems such as the PYROsmart® thermal imaging camera (TIC) system couple thermal imaging with software to allow for automated fire suppression system activation in the event of an unexpected rise in temperature (*Thermal Imaging Cameras Help to Prevent Fires,* n.d.). A passive computer-aided fire detection system could be implemented in EV cargo areas to constantly monitor battery temperatures and detect rises in temperature that could be indicative of a battery entering thermal runaway. If a TIC identifies a battery heating up, it can automatically activate sprinkler systems in the area to cool the battery and prevent ignition.

4.4.3 Fixed Water Systems

Water is the most widely used fire extinguishing agent due to its widespread availability, low environmental impact, and high cooling capacity (Zhang et al., 2022). As a readily available resource, water is inexpensive and can be applied as a mist, through a sprinkler system, or injected as a stream (Yuan et al., 2021). At sea, water is readily available and can be pumped directly into hose lines. Sprinkler and mist systems on ships involve filtration processes and freshwater reserves to prevent salt build-up from obstructing water passage. Both streams and overhead systems have advantages, and their application will vary. As the size of water droplets decreases, the smoke absorption capabilities of water increases. Smaller droplets also provide a greater cooling effect than a stream. Furthermore, smaller droplets also decrease the likelihood of batteries short circuiting due to water's conductivity, as described in Figure 19 (Zhang et al., 2022). A human controlled stream, however, can selectively inject water precisely where it is needed. At any size droplet, however, water is corrosive and electrically conductive, however, and may damage electrical equipment during its application.

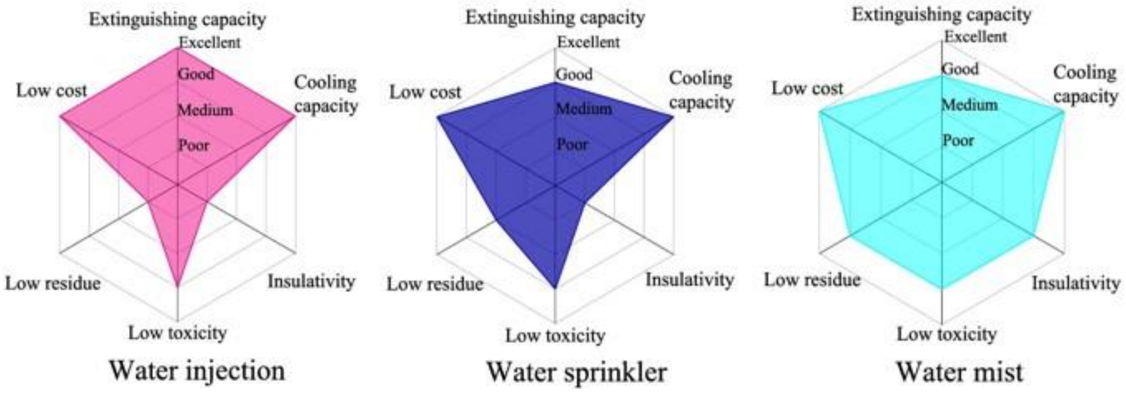


Figure 19. Radar plots of the performances of water in injection, sprinkler, and mist form as a firefighting agent. Extinguishing capacity defines an agent's general ability to extinguish LIB fires and Cooling capacity defines an agent's ability to remove heat from a LIB. Insulativity defines an agent's lack of electric conductivity and Low toxicity defines the agent's environmental and human health impacts. Low residue defines the cleanup required after an agent's use and Low cost defines the financial cost necessary to implement and utilize the agent. *By Shuai Yuan, Chongye Chang, Shuaishuai Yan, Pan Zhou, Xinming Qian, Mengqi Yuan, Kai Liu, 2021, figure included with the express written consent of Elsevier.*

4.4.4 Fixed Water System Additives

Chemical water additives have been developed to improve upon the firefighting capabilities of water. The most used water additives are firefighting foams such as aqueous film forming foam (AFFF) and fluorine free foam (FFF). Both AFFF and FFF are intended to be used on class A (solid materials such as paper) and class B (flammable liquid) fires, with AFFF providing a greater ability to encapsulate objects and extinguish flames at the cost of severe health effects for humans and the environment (Zhang et al., 2022). These health effects include multiple forms of cancer, thyroid disease, and liver and kidney damage, which has led numerous states to move away from AFFF (*NFPA Journal –The PFAS Problem*, 2022). The United States Military plans to halt use of AFFF and implement alternatives, such as FFF, by October 2024. FFF, however, may require twice the foam and extinguishing time of AFFF (*NFPA Journal – The New Foam, 2022*).

Foaming additives in water (Figure 20) utilize hydrocarbon-based surfactants and/or fluorosurfactants (chemicals that lower the surface tension and increase the viscosity of a liquid) to lower the density and increase the viscosity of water (Yuan et al., 2021). These properties allow foam to adhere to the surface of batteries and better isolate the battery from external oxygen than water alone. Foam can be applied to a fire through a fire house or overhead foam suppression system, though both will require extensive cleanup. Moreover, LIB fires extinguished with foam were found to "reignite and burn violently 45 [seconds] after the open flame was extinguished" (Zhang et al., 2022).

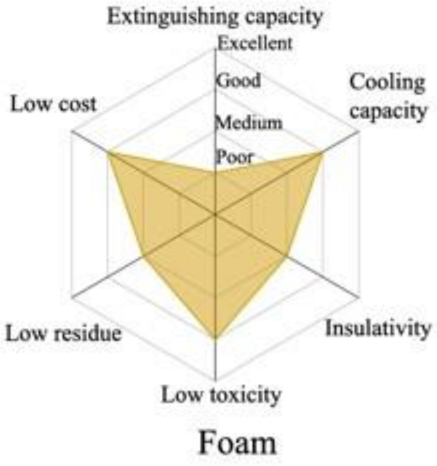


Figure 20. Radar plot of the performance of foam as a firefighting agent. Extinguishing capacity defines an agent's general ability to extinguish LIB fires and Cooling capacity defines an agent's ability to remove heat from a LIB. Insulativity defines an agent's lack of electric conductivity and Low toxicity defines the agent's environmental and human health impacts. Low residue defines the cleanup required after an agent's use and Low cost defines the financial cost necessary to implement and utilize the agent. *By Shuai Yuan, Chongye Chang, Shuaishuai Yan, Pan Zhou, Xinming Qian, Mengqi Yuan, Kai Liu, 2021, figure included with the express written consent of Elsevier.*

Another water additive, F-500 EA, is equally effective when mixed with freshwater or saltwater and can be administered through an injection, sprinkler, or mist system (*Multipurpose Fire Suppression Agent for Class A, Class B, and Class D Fire Types*, 2018). F-500 EA is an encapsulating agent which lowers the surface tension of water, decreasing droplet size and increasing surface area to increase the amount of water that contacts a fire's fuel source. F-500 EA also draws heat toward the center of the water droplet, absorbing more heat energy than water alone (*F-500 Encapsulator Agent Features and Benefits*, 2017). Testing has shown that F-500 EA improves the cooling ability of water by a factor of six to ten, resulting in its recommended use for electric vehicle fires (*F-500 Encapsulator Agent*, n.d.). Furthermore, the encapsulation technology of F-500 EA reduces toxic chemical concentrations in the air and reduces smoke production to increase visibility and air quality (*F-500 Encapsulator Agent [F-500 EA]*, n.d.). F-500 EA is nonconductive, noncorrosive, non-skin sensitizing, and completely biodegradable and can be used in existing sprinkler and mist systems without any need for special equipment or upgrades. For hose line application, F-500 EA can be premixed in a reserve tank or added at the nozzle through an eductor – a device which utilizes suction to draw F-500 EA into the water stream without the need for any moving parts (*F-500 Encapsulator Agent Features and Benefits*, 2017).

4.4.5 Fixed Carbon Dioxide Systems

Carbon dioxide (Figure 21) suppresses fires by displacing the available oxygen in the compartment, suffocating the fire, and preventing the spread of flames. (Xu et al., 2020). Carbon dioxide can suppress LIB fires, but reignition occurs due to its minimal cooling effect (Yuan et al., 2021). In an experiment comparing the efficiency of different fire suppression systems on LIB fires, carbon dioxide was able to extinguish the fire, but exhibited the lowest cooling ability. After carbon dioxide was applied and the flames ceased, the peak temperature of the LIB was lowered an average of 43 °C (109 °F) when compared to the trial in which no extinguishing agents were used. In a similar experiment, where a large LIB was heated to initiate thermal runaway and fire, carbon dioxide was able to extinguish the flames, however the battery reignited soon after being extinguished due to the minimal cooling effect of carbon dioxide (Rao et al., 2015). The application of carbon dioxide is also made difficult by the likelihood of nozzles freezing closed due to the rapid cooling associated with pressure decreases in the delivery systems (Zhang et al., 2022). According to NFPA 12, carbon dioxide systems in spaces smaller than 6000 ft3 can be discharged automatically and must have an alarm and time delay to give those in the affected area time to exit. Carbon dioxide is a dangerous gas that can be lethal in concentrations ranging from 17-30% of the total air in a compartment and all entrances and exits must be gastight as a leak could be deadly (NFPA 12, 2022 Edition). Despite carbon dioxide's limited ability to cool LIB fires, carbon dioxide systems are used on vessels in areas designed for the transportation of vehicles as outlined in 46 CFR and NFPA 12.

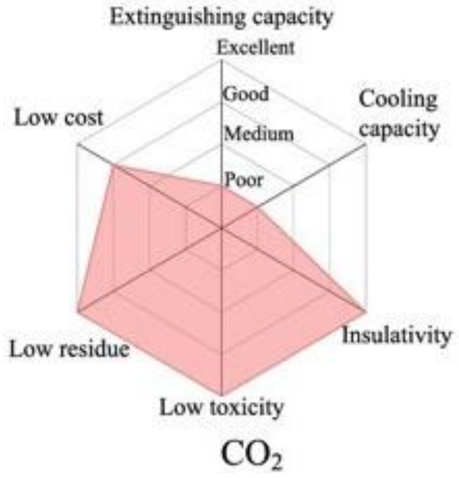


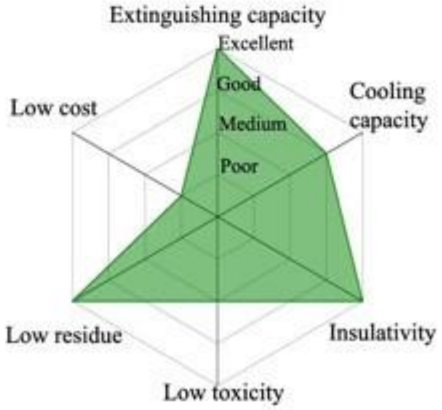
Figure 21. Radar plot of the performance of $CO2$ as a fire extinguishing agent. Extinguishing capacity defines an agent's general ability to extinguish LIB fires and Cooling capacity defines an agent's ability to remove heat from a LIB. Insulativity defines an agent's lack of electric conductivity and Low toxicity defines the agent's environmental and human health impacts. Low residue defines the cleanup required after an agent's use and Low cost defines the financial cost necessary to implement and utilize the agent. *By Shuai Yuan, Chongye Chang, Shuaishuai Yan, Pan Zhou, Xinming Qian, Mengqi Yuan, Kai Liu, 2021, figure included with the expressed written consent of Elsevier.*

4.4.6 Fixed Clean Agent Systems

$C_6F_{12}O$ (Figure 22) is environmentally friendly with an ozone depletion of zero and a global warming potential of one (Pagliaro & Linteris, 2017). Ozone depletion refers to the amount of ozone depleted relative to the compound trifluorochloromethane, and global warming potential is quantified based on the amount of heat absorbed by a compound relative to carbon dioxide. $C_6F_{12}O$ is a non-conductive liquid that vaporizes at 49 degrees Celsius and is often used to extinguish electrical fires (Yuan et al., 2021). As the liquid vaporizes, substantial amounts of heat are removed from the fire (Yuan et al., 2021). Ions released during the decomposition of $C_6F_{12}O$ capture radicals and interrupt the combustion chain reaction to prevent the fire from spreading (Zhang et al., 2022).

In an experiment testing the efficiency of $C_6F_{12}O$, a LIB was heated using a 400 W electric sheet heater until thermal runaway was initiated. Once the fire began, $C_6F_{12}O$ was discharged into the compartment. The fire was extinguished in 2 to 3 seconds and reignition did not take place. The results of the experiment also indicated that an increase in the amount of $C_6F_{12}O$ discharged decreased the amount of smoke and increased the clean agent's cooling effect. The study showed that a large amount of smoke was produced after $C_6F_{12}O$ was applied (Liu et al., 2018). In other experiments where $C_6F_{12}O$ was applied as a precautionary, it was able to reduce the flaming combustion efficiency below 18% and prevented complete thermal runaway in 67% of tests. It is also worth noting that these experiments were conducted when the batteries were at 100% state of charge and 50% state of charge, which implies that the tests would be more successful when the battery is at its typical shipping state of charge of 30% (Said & Stoliarov, 2021).

A disadvantage to $C_6F_{12}O$, is the exacerbation of HF concentrations; in addition to the release of HF by LIBs during combustion, $C_6F_{12}O$ releases fluorine ions when it decomposes (Zhang et al., 2022). In a similar study, the air flow was manipulated when applying $C_6F_{12}O$ to determine the volume percentage necessary to effectively extinguish LIB fires. In this study 12 LIBs composed of 18650 cells were packed together and heated until thermal runaway was initiated, and a fire occurred. When the volume percentage of $C_6F_{12}O$ in the compartment was 8.5%, thermal runaway propagated to all cells and the fire was not suppressed. When the volume percentage of $C_6F_{12}O$ was increased to 15.2%, the rate thermal runaway propagation was reduced and even prevented in 57% of cells (Said & Stoliarov, 2021).



$C_6F_{12}O$

Figure 22. Radar plot of the performance of $C_6F_{12}O$ as a fire extinguishing agent. Extinguishing capacity defines an agent’s general ability to extinguish LIB fires and Cooling capacity defines an agent's ability to remove heat from a LIB. Insulativity defines an agent’s lack of electric conductivity and Low toxicity defines the agent’s environmental and human health impacts. Low residue defines the cleanup required after an agent’s use and Low cost defines the financial cost necessary to implement and utilize the agent. *By Shuai Yuan, Chongye Chang, Shuaishuai Yan, Pan Zhou, Xinming Qian, Mengqi Yuan, Kai Liu, 2021, figure included with the express written consent of Elsevier.*

HFC-227ea (Figure 23) is a gaseous extinguishing agent that has an ozone depletion potential of zero and a global warming potential of 3220, making HFC-227ea a less environmentally friendly option than $C_6F_{12}O$ (Vollmer et al., 2011). HFC-227ea is also low-toxic, making it safe to use in occupied spaces (Fan et al., 2019). HFC-227ea has a stronger cooling effect than carbon dioxide, though it still lacks substantial cooling ability (Zhang et al., 2022). In an experiment comparing the effectiveness of various firefighting agents on extinguishing LIB fires, HFC-227ea was able to extinguish the fire in 23 seconds compared to 30 seconds when using a carbon dioxide system (Xu et al., 2020). Another benefit of using HFC-227ea is that it chemically reacts with LIB fires. Molecules produced by the decomposition of HFC-227ea capture free radicals, and their reduction slows the rate of combustion significantly (Yuan et al., 2021). With the combined cooling effect and ability to interrupt the combustion chain reaction, HFC-227ea is a more effective option to extinguish LIB fires (Rao et al., 2015).

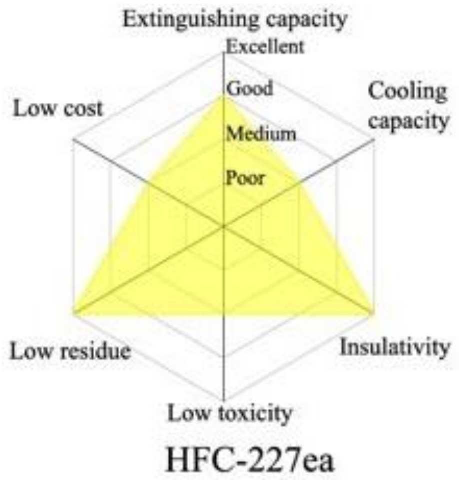


Figure 23. Radar plot of the performance of HFC-227ea as a fire extinguishing agent. Extinguishing capacity defines an agent’s general ability to extinguish LIB fires and Cooling capacity defines an agent's ability to remove heat from a LIB. Insulativity defines an agent’s lack of electric conductivity and Low toxicity defines the agent’s environmental and human health impacts. Low residue defines the cleanup required after an agent’s use and Low cost defines the financial cost necessary to implement and utilize the agent. *By Shuai Yuan, Chongye Chang, Shuaishuai Yan, Pan Zhou, Xinming Qian, Mengqi Yuan, Kai Liu, 2021, figure included with the expressed written consent of Elsevier.*

4.4.7 Portable Extinguishers

Quickly extinguishing a fire before it spreads can save lives and prevent financial loss. Portable fire extinguishers provide an accessible and maneuverable means of quickly suppressing fires. Various fire extinguishing options exist for combatting LIB fires, ranging from traditional ABC (dry chemical powder) extinguishers and water cans to extinguishers designed specifically for LIBs.

The most frequently used fire extinguisher type is a dry chemical extinguisher, commonly rated as an ABC extinguisher (Government of Canada, 2022). Fire extinguishers are rated based on five categories by the NFPA, as seen in Figure 24. Dry powder extinguishers create a mess when used and are not particularly effective against LIBs (Figure 25), however, which contain components of Class A, B, C, and D fires.

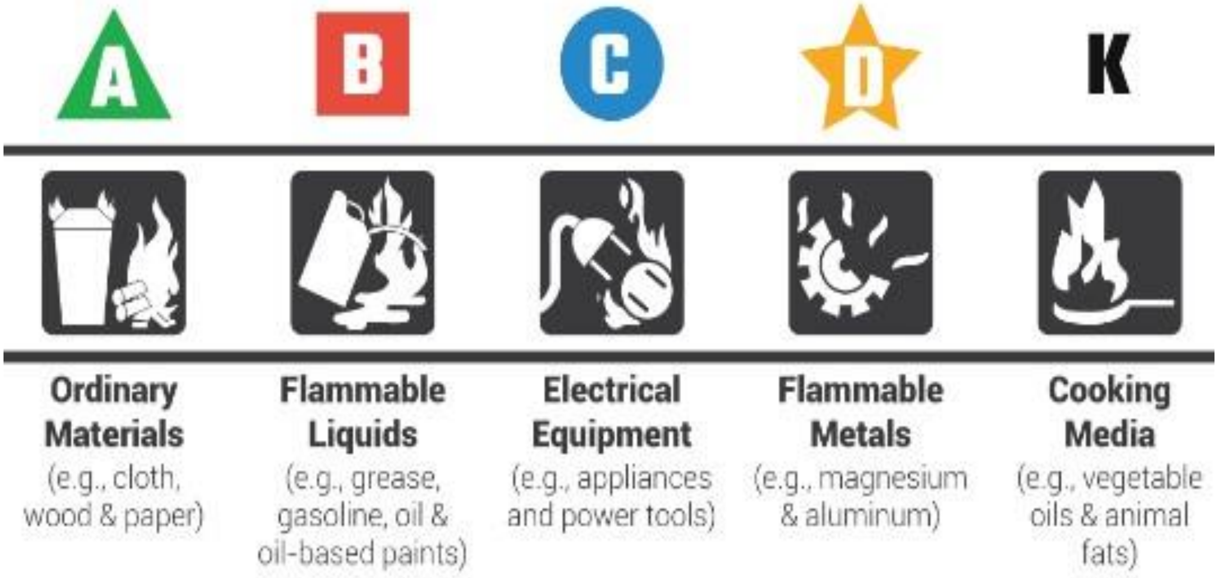


Figure 24. A sign detailing the classifications of fires determined by the NFPA for assistance in choosing an adequate extinguisher for a given fire.
By the City of San Jose, n.d., image is in the public domain.

Figure 25. Radar plot of the performance of dry powder as a fire extinguishing agent. Extinguishing capacity defines an agent's general ability to extinguish LIB fires and Cooling capacity defines an agent's ability to remove heat from a LIB. Insulativity defines an agent's lack of electric conductivity and Low toxicity defines the agent's environmental and human health impacts. Low residue defines the cleanup required after an agent's use and Low cost defines the financial cost necessary to implement and utilize the agent. *By Shuai Yuan, Chongye Chang, Shuaishuai Yan, Pan Zhou, Xinming Qian, Mengqi Yuan, Kai Liu, 2021, figure included with the expressed written consent of Elsevier.*

Water cans are handheld extinguishers used to transport 1.5 to 2.5 gallons of water to a fire (*F-500 Encapsulator Agent Fire Extinguishers*, n.d.). Water cans function like typical ABC fire extinguishers, however the dry powder used to extinguish the fire is replaced with water. These fire extinguishers consist of a metal cylinder filled with water and a pressurized gas, a flexible tube, valve, and handle (Xiaomeng et al., 2010). Once the water can is activated, the valve opens, and the pressurized gas causes the water to be discharged from the extinguisher. The flexible tube allows the user to target a specific region of the fire. Water cans are refillable and additives such as F-500 EA can be added to the water in the cylinder to aid in extinguishing a LIB fire (*F-500 Encapsulator Agent Fire Extinguishers*, n.d.).

Other options include new fire extinguishers designed specifically for LIB fires. One company, Aqueous Vermiculite Dispersion, or AVD, produces an extinguisher it calls Lith-Ex (*Lith-Ex Lithium Battery Fire Extinguishers*, n.d.). AVD extinguishers contain microscopic platelets of vermiculite, a naturally occurring mineral, as a water additive (*What Is Aqueous Vermiculite Dispersion?*, n.d.). The water in the extinguisher cools the battery while the platelets overlap and rapidly dry to create a nonconductive physical barrier to contain the fire. For small, accessible LIB fires, AVD extinguishers can extinguish the fire while only creating a small mess within the immediate area (AVD Fire Extinguisher Solution, 2020).

4.4.8 Solid Agents for Preventing Reignition

Solid firefighting agents can be used to extinguish flames, but the mess associated with their application limits their appeal. An alternative use of solid extinguishing agents is for safely containing damaged batteries at risk of ignition or reignition. Innovative products made by companies such as CellBlockEx and Extover consist of engineered glass granulates and offer promising results. The porous granulates absorb heat, capture gases and vapors, bind liquids, and smother flames ("Extinguishing with Expanded Glass – Extover® Fire Extinguisher for Lithium Battery Fires and Metal Fires," 2021). At elevated temperatures, the granules will melt and create an impermeable barrier ("CellBlockEX," n.d.). Batteries being shipped as cargo, especially those that are damaged, can be shipped in containers filled with the glass granulates, preventing incidents from spreading should they occur. The granulates are also reusable and environmentally friendly, making them an intriguing option for containing LIB fires ("Extinguishing with Expanded Glass – Extover® Fire Extinguisher for Lithium Battery Fires and Metal Fires," 2021).

4.5 Feasibility of Proposed Practices

4.5.1 Enforcement

An area of importance when considering the practicality and feasibility of a proposed policy is the ability of the USCG to properly enforce it. A policy that cannot be enforced is ineffective and will not help solve the problem. An interview with Lieutenant Commander Kelley Brown of the USCG Commercial Vessel Compliance Division (CG-CVC) (Appendix B) was conducted in-person at the United States Coast Guard headquarters on the St. Elizabeth's Campus in

Washington, DC. This interview focused on existing regulations for LIB use on small passenger vessels (SPVs), and the challenges of enforcing these regulations due to the transient nature of commercial SPVs. The policy letter Carriage of Lithium-Ion Batteries on Small Passenger Vessels outlines recommendations for personal-use LIBs on SPVs. LCDR Brown stated that she does not believe the policy for LIBs falls short on SPVs; rather, she believes the challenge comes in enforcement. On commercial SPVs, passengers often bring LIBs onboard in personal devices, which makes safety enforcement difficult for marine inspectors (MIs), since they almost always conduct inspections when passengers are not onboard. MIs will instead ask the crew questions surrounding the hazards of LIBs to ensure they are knowledgeable about the dangers and prepared to respond in the event of a LIB fire. LCDR Brown stated that it is difficult for vessel owners and crew members to enforce LIB regulations on SPVs since they have no knowledge of the condition of the chargers or batteries that passengers bring onboard. The difficulty in enforcement on SPVs could mean that increased personal agency may be necessary to better prevent LIB fires. Increased personal agency could come from increased awareness, making sure passengers are aware of the dangers and aware of the best practices that the USCG recommends.

4.5.2 Legal Jurisdiction

Title 49 of the CFR is under the authority of the Department of Transportation (DOT). The USCG works with the DOT in maritime enforcement of Title 49 regulations and collaborates with the DOT's Pipeline and Hazardous Materials Safety Administration (PHMSA) on relevant regulations. The Coast Guard is unable to directly regulate the policies in Title 49 however given this distinction. This lessens the direct impact of any proposed policies regarding the packaging and transport of LIBs, as those areas fall under the DOT's jurisdiction.

5. Conclusions and Recommendations

This section outlines a set of recommendations to the United States Coast Guard to revise and update policies and practices regarding LIBs on SPVs and Ro-Ro carriers.

5.1 General Recommendations

1. Adopt the aviation industry’s 30% maximum state of charge for shipped standalone lithium-ion batteries.

A higher SOC in a LIB can be associated with a lower ignition temperature, higher HRR, higher maximum temperature, and faster rate of toxic gas release. We recommend that the marine shipping industry adopt the aviation industry’s 30% maximum SOC for standalone LIBs to reduce the likelihood of fires igniting and limit the gases and heat energy released by the battery if ignition does occur.

2. Educate crews on the dangers of improper charging practices.

We recommend that crew members receive the proper education on unsafe charging practices such as daisy chaining, charging a damaged device, or using an improperly rated charger that has not been independently tested. While an SPV is underway, crewmembers will be responsible for ensuring that the proper LIB practices are followed by the passengers, so keeping them fully informed on the dangers of improper charging will help them properly enforce the relevant policies and practices.

3. Educate crews on the unique dangers of a LIB fire.

Crews on passenger and cargo vessels receive basic firefighter training and engage in regular drills, but the unique dangers of LIB fires demand specific attention. LIBs do not burn the same as traditional building materials. Using conventional firefighting practices without understanding the risks associated with LIB fires can result in unsuccessful firefighting efforts coinciding with human injury and exacerbated financial loss. Further education for crews regarding the response to LIB fires should involve two main ideas. First, crews should be aware of the hazardous byproducts that offgas from LIBs during thermal runaway and after ignition. These gases include HF and CO, which are toxic and can be fatal. SCBAs should always be worn in all environments when attempting to extinguish a LIB fire. Additionally, LIBs are at risk of explosion with ejecta during a fire incident and can result in physical injury while also rapidly spreading the fire.

The second topic to be covered should be the significant risk of LIB fires reigniting after being extinguished. Because thermal runaway cannot be stopped in cells where it is already occurring, the cell will continue to heat itself until the energy of the cell is depleted. For this reason, crews will have to be aware of the need to constantly cool a LIB after a LIB fire is extinguished to prevent it from reigniting. Crews should also know how to handle and safely package extinguished LIBs. Whether a battery is continuously cooled or is fully contained, crews must also be made aware of the need to constantly monitor the damaged battery so that reignition may be prevented or quickly responded to.

4. Require testing of used and aging batteries.

Used and aging batteries are at greater risk of failure than new batteries. Cells and batteries are only tested within the first six months of their creation. Their level of safety as they progress through their life cycle is unknown. We recommend that the USCG draft policy requiring manufacturers to test their cell and battery products after specified amounts of time and use. This will ensure that the batteries are safe throughout their intended lifespan.

5. Require lithium-ion battery system manufacturers to provide electrolyte-specific firefighting agents.

The chemistry of specific electrolytes determines the chain reactions present in combustion and the free radicals released by the battery. Firefighting agents can be developed to counteract specific chemical reactions; however, the chemistries of the electrolytes are considered proprietary knowledge by most manufacturers and are kept confidential. We recommend requiring every manufacturer producing LIB systems for marine use to either release the chemistries of their battery components or also provide a firefighting agent along with each specific product. The disclosure of battery component chemistries, or even the chemistry of their designed firefighting agent, may receive pushback from manufacturers trying to maintain confidentiality, but the need to extinguish fires quickly and protect human safety must be prioritized.

6. Influence the drafting of NFPA code 401, Chapter 12: Battery Cells and Waste.

The NFPA is currently drafting codes for batteries, including LIBs. NFPA 401: Recommended Practice for the Prevention of Fires and Uncontrolled Chemical Reactions Associated with the handling of Hazardous Waste is in the preliminary stages of development. Chapter 12: Battery Cells and Waste, has only rudimentary recommendations within it. We recommend that the USCG drafts contributions and submits them to be included within the code. Because the code is in such an early stage, we believe the USCG can provide significant contributions to the document.

7. Monitor the progress and development of stable battery chemistries.

As research into more stable battery chemistries progresses, these batteries may develop into viable alternatives to current LIB chemistries. The development of safer components such as $LiFePO_4$ cathodes and solid-state electrolytes would lead to less risk of LIB fires. We recommend the USCG monitor the progress of this field of research and adjust their policies and assessment practices as necessary.

5.2 Recommendations for Small Passenger Vessels

We found the existing policy surrounding LIBs on SPVs to be adequate, but difficult to enforce. Outlined here are recommendations to address this challenge based on the results of this research.

8. Require markings and cautionary signage for appropriate charging areas.

Based on LCDR Brown's comments on the difficulty of MIs and vessel owners enforcing LIB best practices on SPVs due to the transient nature of the passengers, we recommend requiring markings and signage to identify designated charging areas on SPVs. In the Carriage of Lithium-Ion Batteries On Small Passenger Vessels policy letter, it is recommended that charging only occur in regularly occupied spaces or spaces fitted with smoke detection systems. By properly marking these locations on SPVs, passengers will be aware of the designated locations and improper charging practices will be easier to avoid.

A further step in increasing passenger awareness would be requiring signage in charging locations warning passengers of the dangers of improper charging. A sign in a charging location would tell passengers to avoid charging their device if it is wet or damaged and to remove their device when it is fully charged.

We also recommend requiring SPVs to include LIB charging dangers and protocols in a safety brief while the vessel is departing port, similar to a safety brief in the aviation industry before a plane takes off. Increasing passenger awareness will help vessel owners ensure proper charging practices and lessen the risk of a fire due to improper charging.

9. Continue to follow current practices when assessing battery propulsion systems.

As LIB propulsion systems become more common in SPVs, proper design and construction is critical to preventing LIB fires. Currently, the MSC follows the Design Guidance for Lithium-Ion Battery Installations Onboard Commercial Vessels policy letter, as well as ASTM F3353-19: Standard Guide for Shipboard Use of Lithium-Ion Batteries when assessing vessel design plans. We found these documents to be sufficient in structural fire protection, battery management system and fire-fighting system requirements. We believe the USCG should continue to follow these guidelines and do not think they are the cause of the issue.

10. Require vessels to carry DOT-approved lithium-ion battery containers to store at-risk or previously ignited batteries.

If a LIB ignites on a vessel, and even if the flame is extinguished, it will require special attention due to its risk of reignition. We recommend requiring vessels to carry a DOT-approved solid agent such as CellBlockEx or Extover to place LIBs in if they enter thermal runaway or ignite while underway. Certain solid agents can keep passengers safe from the toxic gases released and contain the fire if the battery reignites. A potential option could also be sand, but sand would not capture the toxic gases, so additional measures such as PPE would be necessary when opening the container. A container of water would cool the battery as well; however, it would also not contain the toxic gases.

5.3 Recommendations for Ro-Ro Carriers

We found the existing policy regarding LIBs on Ro-Ro carriers to be generic and outdated. The uniqueness and novelty of LIB fires necessitates targeted and updated policies. Outlined here are a set of recommendations to address this issue based on the results of this research.

11. Require a state of charge of no greater than 50% when transporting EVs.

To decrease the severity of LIB fires on vessels, we recommend that LIBs used to power EVs are maintained at a SOC of 50% or less during transportation. A higher SOC can result in a higher peak temperature during fires, cause the battery to ignite at a lower temperature and can result in the production of dangerous gases at a faster rate. Requiring a lower SOC when transporting EVs also makes it easier to extinguish an LIB fire when it occurs, as a lower SOC is related to a shorter time to extinguishment. For a battery's health and lifespan, it is best to keep the SOC of the battery between 20% and 80%. A maximum SOC of 50% should be used to account for the charge that EV batteries lose during long voyages overseas, while the optimal range for SOC would fall between 20% and 30%.

12. Require a minimum of six feet between vehicles during transportation.

As mentioned in 4.3.3, there are currently no regulations defining a minimum distance vehicles must be kept from each other on carrier vessels. This prompts manufacturers to have the ships packed with vehicles as tightly as possible, leaving no room for crews to navigate between them. This greatly increases the risk of a LIB fire spreading between vehicles and makes it extremely difficult to reach interior vehicles when they ignite. For these reasons, we recommend creating regulations that establish a minimum distance of six feet that vehicles, and especially EVs, must be kept from each other during transit. This regulation would not only lessen the spread of a fire, but it would also make it easier for a responder to access that fire. Having adequate space for responders to quickly reach a fire while in full PPE and while dragging hose lines or carrying portable extinguishers is necessary to extinguishing a fire while it is small. This recommendation will likely receive resistance from manufacturers because it would result in an increase in their shipping costs, but any compromises made should still allow for the unhindered navigation of individuals between vehicles.

13. Increase the frequency of safety patrols in EV cargo areas.

Crews are required to complete safety patrols as mandated through 46 CFR. In cargo areas containing EVs, however, the frequency of these patrols should be increased, and at least one crew member should always be patrolling these areas. Through a workshop with the ABS, a majority of experts agreed that increasing safety patrols was a good practice in areas containing EVs. Infrequent safety patrols make it difficult to detect a LIB fire in its early stages when it is easiest to cool and extinguish the fire. As the fire continues, it could quickly spread to nearby vehicles and produce toxic gases, amplifying the risk of injury and complete loss as the fire grows. Early detection through increased safety patrols can save lives and cargo if the fire is spotted quickly and action is taken to extinguish the fire.

14. Implement the use of thermal imaging devices in EV cargo areas.

Early identification of overheating batteries is important for preventing thermal runaway and ignition. We recommend the use of stationary thermal imaging cameras in EV cargo areas to consistently monitor the temperature of each vehicle and alert the crew if the temperature of a vehicle gets too high. If this implementation is not possible, it is also sufficient to require safety patrols to carry a thermal imaging device so they can monitor the temperatures of vehicles onboard. Utilizing both methods in conjunction with one another would be ideal. This recommendation was also considered at the aforementioned ABS workshop and was highly approved by ro-ro stakeholders and experts.

15. Train crews to be prepared to fight an EV fire onboard a vessel.

Crew members are required to complete basic firefighting training, but this training does not address the unique risks of LIB fires on vessels. The LIBs that power EVs are often found underneath the vehicle, making it difficult to reach the seat of the fire. Skills such as bouncing the stream from a fire hose off the deck of a ship and into an EV battery should be practiced to train crews to fight EV fires. Crews should also train to identify the dangers of reignition by using thermal imaging cameras once LIB fires are extinguished.

16. Require water mist systems in cargo areas transporting EVs.

Water mist systems should be implemented in cargo areas used to store EVs during transportation. Some systems that are currently in place on vessels in areas designated for the transportation of vehicles include water sprinklers and carbon dioxide systems which have had limited success in extinguishing LIB fires due to a poor cooling ability. Water mist systems utilize small water droplets to improve the smoke absorption and cooling capabilities of water. Decreasing the size of water droplets increases their relative surface area and allows a greater amount of water to contact the fire and evaporate, removing a substantial amount of heat and thus cooling the fire. Water mist systems can cool objects around the fire to prevent the spread of fire from one area to another. As shown in Figure 19, water mist also has better insulative properties and lower residue than water injections and streams, decreasing the likelihood of further reignition due to short circuiting of the battery or surrounding batteries. Water is readily available in tanks onboard vessels and salt water can be filtered and pumped through the system to extinguish the fire if needed.

17. Require upward facing sprinklers on Ro-Ro decks transporting EVs.

Unlike vehicles powered by internal combustion engines, the battery used to power an EV is located under the body of the vehicle. When an EV battery begins heating up and enters thermal runaway, the body of the vehicle shields the battery from water released by overhead sprinklers. Upward facing sprinkler systems built into the decks of Ro-Ro carriers containing EVs would allow for water to be directly applied to the battery and effectively cool batteries even before ignition.

18. Implement encapsulating agents as a water additive in fire protection systems.

Water additive encapsulating agents such as F-500 EA should be implemented into fire protection systems in areas where LIBs are present. Encapsulating agents as water additives can reduce the smoke and toxic gases present in the air, providing for greater visibility and making the air safer to breathe around LIB fires. Agents that also reduce the surface tension of water, such as F-500 EA, increase the cooling capability of water while the encapsulating agents inhibit chemical chain reactions. Hindering two aspects of the fire tetrahedron will greatly increase a system's ability to suppress and extinguish LIB fires.

19. Phase out carbon dioxide systems by implementing gaseous encapsulating agent systems.

Carbon dioxide systems are permitted for use in areas containing vehicles under 46 CFR and are advised for use through fire code NFPA 12. However, carbon dioxide has a low cooling capability and has proven to be ineffective at extinguishing LIB fires. Automatic carbon dioxide systems require a discharge alarm and time delayed release which can allow a fire to grow as crew members evacuate the area. Gaseous encapsulating agents such as $C_6F_{12}O$ and HFC-227ea have better cooling capacities than carbon dioxide and work by capturing free radicals to interrupt the combustion chain reaction that allows fires to burn. Both gases can be effective in concentrations not harmful to humans and are more effective than carbon dioxide when extinguishing LIB fires. $C_6F_{12}O$ also has a minimal environmental impact. Carbon dioxide systems should be phased out and replaced with gaseous encapsulating agent systems in areas on vessels containing EVs.

5.4 Recommendations for the Department of Transportation

Although not directly under the jurisdiction of the United States Coast Guard, there are areas in Title 49 of the Code of Federal Regulations that have room for improvement.

20. Refine definitions of used, recycled, damaged, defective, and recalled batteries.

Currently, regulations primarily address new LIBs, while regulations for used, recycled, defective, and damaged batteries are less defined. These batteries may pose a larger fire risk than new batteries in transportation, so better descriptions and definitions to help shippers properly identify them would be beneficial. Clearer definitions may focus on necessary testing, characteristics of the batteries, and necessary precautions when transporting them.

21. Increase consistency across regulations of different transportation modes.

LIBs may be shipped by road, rail, air, or vessel, and often will travel by multiple modes during the shipment process. Currently, there are notable differences in the restrictiveness of regulations between modes, with road and rail being less strict than vessel and air being the most strict. These differences in regulation can increase risk when transferring cargo from a less strict mode to a stricter mode, such as a truck transporting cargo to a vessel for shipment. Increasing harmony would lower this risk and ensure safer shipments. We recommend the USCG work with the Federal Aviation Administration and the Pipeline and Hazardous Materials Safety Administration to harmonize these regulations across transport modes.

5.5 Future Research

Further research should be conducted to assess crew and passenger awareness of the dangers of LIBs. A survey should be distributed to crew members that contains questions about proper handling and charging practices for LIBs, regulations governing the transportation and shipping of LIBs, the hazards associated with LIB fires, and the proper response required when a LIB fire occurs. A survey should also be distributed to passengers covering proper charging practices and hazards associated with LIBs. These surveys can be used to determine which areas of LIB safety should be reinforced in crew training and if measures such as additional signage should be required on SPVs to increase passenger awareness of LIB safety.

A financial analysis can be completed to determine the monetary impact of increasing the spacing between vehicles on Ro-Ro carriers. Increasing the space between vehicles decreases the risk of the fire spreading to other objects, however, there may be a substantial financial loss for shippers and manufacturers due to the decrease in the number of vehicles that can be transported per shipment. Pushback from shippers is likely to take place if the spacing requirements are updated. A financial analysis can be used to determine how much space between vehicles on Ro-Ro carriers is feasible for shippers while mitigating the spread of fire during transportation.

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Appendix A:

Informed Consent Agreement for Participation in a Research Study

Investigator: Professor Fred Looft, PhD; Professor Linda Looft, Owen Radcliffe, Joe Peregrim, Keith Mesecher, Ryan Malaquias
Contact Information: gr-dc22-uscg@wpi.edu, lclooft@wpi.edu, fjlooft@wpi.edu
Title of Research Study: Recommending Measure for Preventing and Responding to Lithium-ion Battery Fires at Sea
Sponsor: United States Coast Guard

Introduction

You are being asked to participate in a research study. Before you agree, however, you must be fully informed about the purpose of the study, the procedures to be followed, and any benefits, risks, or discomfort that you may experience as a result of your participation. This form presents information about the study so that you may make a fully informed decision regarding your participation.

Purpose of the study:

The purpose of this study is to assess existing safety standards and firefighting practices related to lithium-ion battery fires with the purpose of recommending best practices and policies to the United States Coast Guard to prevent and mitigate lithium-ion battery fires onboard passenger vessels and roll-on-roll-off carriers.

Procedures to be followed:

We will be interviewing groups of experts to gain a deeper understanding of existing safety standards and firefighting practices/assess the validity of our proposed policies and best practices. As a participant, the duration of your participation is only this interview session, which is expected to last 30 minutes. Nothing will be expected of you outside of this session.

Risks to study participants:

There are no risks to participating in this study.

Benefits to research participants and others:

There are no benefits to participation, the interviews are solely to gain information for our study.

Record keeping and confidentiality:

Recordings of the interview sessions will be kept in a private Microsoft Teams channel accessible only by the primary investigators and four student investigators. Recordings may be shared with the United States Coast Guard. The study investigators, the sponsor or its designee and, under certain circumstances, the Worcester Polytechnic Institute Institutional Review Board (WPI IRB) will be able to inspect and have access to confidential data that identify you by name. Your identity and qualifications will be disclosed in any publication of this study, but any other personal information will be kept confidential.

Compensation or treatment in the event of injury:

No injuries should be suffered during participation. You do not give up any of your legal rights by signing this statement.

For more information about this research or about the rights of research participants, or in case of research-related injury, contact: Professor Fred Looft, PhD at fjlooft@wpi.edu, Professor Linda Looft at lclooft@wpi.edu, the WPI IRB Chair Professor Kent Rissmiller, Tel. 508-831-5019, Email: kjr@wpi.edu or the WPI University Compliance Officer Gabriel Johnson, Tel. 508-831-4989, Email: gjohnson@wpi.edu.

Your participation in this research is voluntary.

Your refusal to participate will not result in any penalty to you or any loss of benefits to which you may otherwise be entitled. You may refuse to answer any question that is presented to you without penalty or loss of other benefits. You may decide to stop participating in the research at any time without penalty or loss of other benefits. The project investigators retain the right to cancel or postpone the experimental procedures at any time they see fit. By signing below, you acknowledge that you have been informed about and consent to be a participant in the study described above. Make sure that your questions are answered to your satisfaction before signing. You are entitled to retain a copy of this consent agreement.

_____________________________ Date: ____________________

Study Participant Signature

____

Study Participant Name (Please print)

_______________________________________ Date: ____________________

Signature of Person who explained this study

Appendix B:

Interview Protocols for the USCG Commercial Vessel Compliance Division

The table below outlines the questions asked to the USCG Commercial Vessel Compliance Division during the vessel compliance SME interview conducted.

Focus Area	Examples of Questions and Probes
Policy Enforcement	• How does the Coast Guard enforce safety policies? • What challenges does the Coast Guard face in enforcing policies? • How often do MIs find small passenger vessels that are incompliant with the storage, charging and use guidelines outlined in the Carriage of Lithium-Ion Batteries on Small Passenger Vessels policy letter the CVC published? • How common is daisy chaining or similar dangerous practices on SPVs? • How does the CVC enforce battery testing policies? • During inspections, how often are crews aware of the dangers of LIB fires and aware of how to extinguish them? • Do specified charging areas have increased fire safety requirements? • Are there fines for unsafe practices on SPVs or are vessel owners just given a citation and told to fix the issue? If there are fines, what are they? Are they scaled? •
Policy Adoption	• The policy letter published by the CVC focuses on T and K boats (small passenger vessels), are there any analogous policies for I boats, Cargo and Miscellaneous Vessels? • How are new policies adopted? • How do international standards affect policy adoption? • Is there a compliance window that companies have before the new policies begin to be enforced?

Appendix C:

Interview Protocols for the USCG Hazardous Materials Division

The table below outlines the questions asked to the USCG Hazmat Division during the bulk solids and packaging hazmat SME interview conducted.

Focus Area	Examples of Questions and Probes
Current Policy	• Are there areas in which current shipping regulations can be improved with li-ion batteries? • Who has more say in how LIBs are packaged between the Coast Guard and the manufacturers? • Are there regulations for how far apart units of cargo containing LIBs must be? Does that change with what kind of cargo it is (EVs, personal devices, etc.) • How does the dynamic environment of being on a vessel affect packaging regulations compared to a static warehouse? • What qualifies a vessel for a DOT special exemption permit? Do you see incidents occurring in ships that were granted special permits?
Policy Enforcement	• How do companies circumvent shipping regulations and what are the dangers of such activity? I.e. declaring lithium batteries as spare parts. What are the punishments for not following these regulations? • Why might companies try to circumvent LIB shipping regulations? Is there additional cost with shipping hazardous materials or is there a lack of awareness? • What scope of policy can CG-ENG regulate realistically?
Fire Characteristics	• What types of lithium batteries are more prone to thermal runaway? • There is a method of gas detection which involves coupling gas chromatography with Fourier transform infrared spectroscopy, would you be able to provide insight on those two methods and how they may work together? • What is the most common cause of thermal runaway in shipped lithium batteries? • How common is fire spread in cargo holds? Do different regulations govern hazardous materials in cargo holds vs on a weather deck? Do fires spread differently?

Appendix D:

Interview Protocols for the NYS Office of Fire Prevention and Control

The questions in the table below are the questions asked to firefighting SMEs from the NYS Office of Fire Prevention and Control.

Focus Area	Examples of Questions and Probes
Firefighting methods	• Are there currently any set protocols for fighting lithium-ion battery fires? • What protective equipment should be brought to a lithium-ion battery fire?
Firefighting Training	• How are firefighters currently being trained to assess and fight lithium-ion battery fires? • How might this training change if assessing a lithium-ion battery fire on a vessel? • Are there any trainings that are required to be completed before a firefighter can participate in extinguishing flames on a fire scene? • Crew members on ships may only receive basic education regarding firefighting, but they are expected to respond to incidents themselves when the vessel is out at sea. What are some of the most critical areas these crew members should be trained in so that they can effectively respond to a fire? • Are there any risks of expecting individuals with limited training to fight fires, both on open or closed decks or within rooms such as an engine room? • How frequently do you believe individuals should receive training or education to adequately maintain their knowledge and ability to fight a fire, particularly a LIB fire, onboard a vessel?

Appendix E:

Group Interview Protocols for the USCG Marine Safety Center

The table below outlines the questions asked to a vessel design SME from the USCG Marine Safety Center in an interview.

Focus Area	Examples of Questions and Probes
Policies	• What policies regulate the installation of lithium-ion batteries as propulsion systems on vessels? • Are there any flaws to these policies? If so, what do you think these flaws are? • Are there any special considerations in designing cargo holds that transport hazardous materials? • If so, what are they? Do you think they fall short? If you do, how would you alter those designs? • What are the typical fire suppression systems found on vessels that transport hazardous materials? • What are the typical fire detection systems found on vessels that transport hazardous materials? • Are there any major contradictions between US design requirements regarding LIBs and any other foreign policies?
Structural Fire Protection	• How much does the intention to mitigate the spread of a fire factor into the design of a ship? • Are there any specific design features incorporated into ship design with the intention of preventing the spread of a potential fire?

Appendix F:

Interview Protocol for WPI Professor Milosh Puchovsky

The table below outlines the questions asked to Professor Milosh Puchovsky, a fire protection engineering SME, in an interview conducted with him.

Focus Area	Examples of Interview Questions
Effectiveness of Fire Suppression Agents	• Do you know of any alternative firefighting agents that are effective against lithium-ion batteries? • Do you have any knowledge of hybrid gas-water fire extinguishing systems? • Do you think a hybrid gas-water system could be effective?
Risk Assessment	• How do risks get assessed and quantified when evaluating the fire protection system for a battery energy storage system?
Fire Protection Systems	• How would you design a fire protection system for an area in which the source of the fire would be obstructed from a fixed sprinkler system? • Is there currently an industry standard for containing or venting toxic and flammable off-gases? • Do you think a proper ventilation system could lower the risk of an explosive buildup of flammable off-gases? • Are there any effective fire detection systems for lithium-ion batteries? Are there any systems that can detect thermal runaway before ignition?
Battery Chemistry	• Are there any battery chemistries that are common in the lithium-ion battery industry? • Are there any off-gases that are common in the lithium-ion battery industry?