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

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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.

References

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