



# Acquisition Directorate

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## Research & Development Center

# Lithium Battery Fire Hazards in the Maritime Environment

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April 2025



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# Lithium Battery Fire Hazards in the Maritime Environment

## White Paper Documentation Page

1. Report No.		2. Government Accession Number		3. Recipient's Catalog No.	
4. Title and Subtitle Lithium Battery Fire Hazards in the Maritime Environment				5. Report Date April 2025	
				6. Performing Organization Code Project No. 1046	
7. Author(s) J. Pennington				8. Performing Report No.	
9. Performing Organization Name and Address U.S. Coast Guard Research and Development Center 1 Chelsea Street New London, CT 06320		10. Work Unit No. (TRAIS)			
12. Sponsoring Organization Name and Address COMMANDANT (CG-ENG-4) US COAST GUARD STOP 7506 2703 MARTIN LUTHER KING JR AVE SE WASHINGTON, DC 20593				13. Type of Report & Period Covered Interim, November 2024 – April 2025	
				14. Sponsoring Agency Code Commandant (CG-ENG-4) US Coast Guard Stop 7509 Washington, DC 20593	
15. Supplementary Notes The RDC's technical point of contact is Mr. Joshua Pennington, 860-271-2866, email: <a href="mailto:Joshua.D.Pennington2@uscg.mil">Joshua.D.Pennington2@uscg.mil</a> .					
16. Abstract (MAXIMUM 200 WORDS) This is an information document for U.S. Coast Guard (USCG) search and rescue units, USCG Sector response and prevention personnel, National Strike Force members, and other government or commercial response personnel that may interact with lithium-ion battery (LIB) fires in the maritime environment. Additionally, RDC recommends this guidance be shared with commercial vessels with maritime batteries, and vessels that transport electric vehicles and/or electric micromobility devices such as electric bikes and electric scooters. In this paper, the RDC consolidates information and statistics from peer-reviewed journals, industry guidance documents, government reports, and classification society databases to introduce maritime LIB use trends, LIB fire and post-fire hazards, and current fire suppression techniques and equipment. Furthermore, RDC provides safety recommendations for the crews of vessels equipped with or carrying high capacity LIBs, response considerations for personnel encountering LIB fires, and emphasizes use of adequate personal protective equipment in fire and post-fire scenarios.					
17. Key Words Battery fire, battery fire suppression, battery-powered vessel, electric micromobility device, electric vehicle, electric vessel, hybrid vessel, lithium-ion battery, marine battery, maritime battery, thermal runaway, thermal runaway effluent gas			18. Distribution Statement Distribution Statement A: Approved for public release; distribution is unlimited.		
19. Security Class (This Report) UNCLAS//Public		20. Security Class (This Page) UNCLAS//Public		21. No of Pages 22	22. Price



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## 1 INTRODUCTION

Timely delivery of this product to our maritime partners and field units is imperative to mitigate potential harm during and following a lithium-ion battery (LIB) fire response. This paper provides maritime LIB fire hazard information applicable to vessels with maritime batteries, vessels transporting electric vehicles (EVs) or electric micromobility devices (e.g., electric bikes, electric scooters), United States Coast Guard (USCG) search and rescue (SAR) units, Sector response and prevention personnel, National Strike Force members that may interact with these vessels, other response personnel, and commercial assistance services.

In this paper, the term *maritime battery* refers to a rechargeable cell, battery, or battery module(s) used to provide or augment propulsion power and/or electrical services for a battery-powered vessel. The primary categories of battery-powered vessels are hybrid and full electric vessels. Hybrid vessels function similarly to hybrid automobiles and rely on battery power as well as a conventional internal combustion engine (ICE) for propulsion (Ghosh, 2025). Full electric vessels operate solely on battery power and must connect to an external power source to recharge (Wärtsilä, 2025). Hybrid systems may be advantageous for vessels on long routes, with large and/or variable energy demands, or when calling on ports lacking adequate shoreside infrastructure for electrical charging (Ghosh, 2025). Full electric systems may be better suited for fixed routes (e.g., ferries) or for vessels that routinely moor at facilities equipped with shoreside charging stations (Wärtsilä, 2025).

The worldwide battery-powered vessel fleet grew from 142 vessels in 2017 to 1006 vessels in 2024, with an additional 1584 confirmed orders for battery-powered vessels through 2027 (DNV, 2025)<sup>1</sup>. At the time of publication approximately 6% of that fleet are flagged by and operate in the United States (U.S.); however, the U.S. electric fleet is expected to grow as charging infrastructure is developed (Bei et al., 2024; Moon et al., 2024). Increasing numbers of foreign-flagged deep draft vessels are being retrofit with hybrid systems for peak shaving<sup>2</sup>, low power operations, and dockside power applications (DNV, 2025; Wärtsilä, 2025). Ferries are prominent in the battery-powered fleet, but many vessel types are implementing this technology (Figure 1).

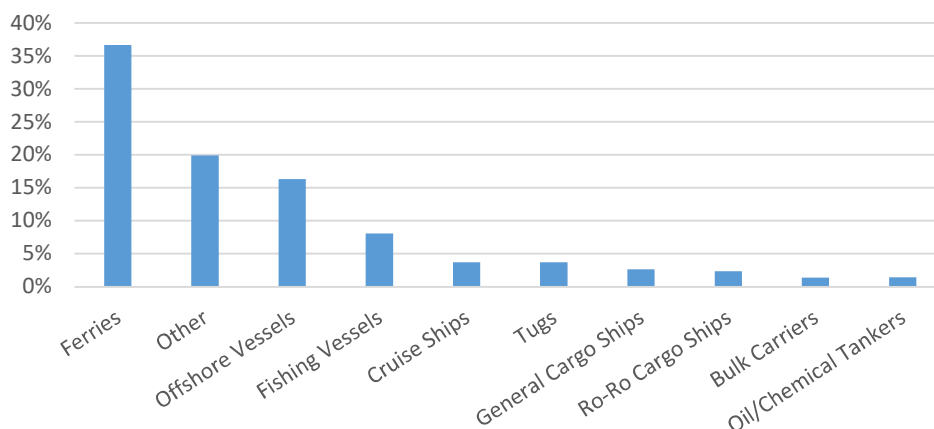


Figure 1. Worldwide battery-powered fleet (2024) by vessel type (DNV, 2025).

<sup>1</sup> Statistics are for classed vessels and do not include unclassified recreational craft.

<sup>2</sup> Peak shaving is a hybrid application that permits an ICE to operate at maximum fuel efficiency by maintaining uniform power output. Battery power is applied when the vessel's power demand exceeds the power provided by the ICE (Wärtsilä, 2025).

Additionally, the number of EVs and electric micromobility devices transported by commercial vessels continues to increase, requiring vessel crews and USCG SAR units to be aware of the hazards particular to LIBs and battery fires (ABS, 2022; NYC DOT, 2025; Liotta, 2025).

### 1.1 RDC Project Background

The USCG is the regulatory body for U.S. maritime commerce, commercial shipping, and oversight of recreational boating standards. Equipment manufacturers offer a variety of vessel electrification solutions using large capacity maritime batteries. The use of commercial maritime battery propulsion and energy storage systems, as well the number of EVs and electric micromobility devices on commercial vessels (e.g., ferries) is rapidly increasing. In response, CG-ENG-4 requested the USCG Research and Development Center (RDC) to investigate LIB technology, battery fire behavior, battery fire suppression, and personnel risks.

## 2 BATTERY DESCRIPTION

### 2.1 Battery Basics

A battery is one or more electrochemical cells designed to provide energy at predetermined voltage and current levels (Beard, 2019). Generally speaking, a cell consists of an anode, a cathode, electrolyte, and an electrically isolating barrier called a separator. During discharge, electrons flow from the negative electrode (anode) to the positive electrode (cathode) through an external circuit (e.g., equipment), while the electrolyte allows for the exchange of ions between the electrodes within the cell through the separator (Linden et al., 2019) (Figure 2).

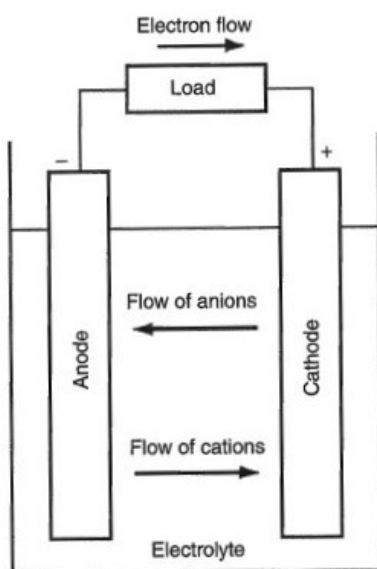


Figure 2. Galvanic battery cell during discharge (Linden et al., 2019).

Electrolyte can be liquid, solid, or gel form, though commercial LIBs commonly use liquid electrolyte (Mulani, 2023). The electrochemical process in commercial LIBs using liquid electrolyte is akin to that of a lead-acid wet cell battery; however, the internal construction of these cells is significantly different.



## Lithium Battery Fire Hazards in the Maritime Environment

Two prevalent classifications of batteries are *primary batteries* and *secondary batteries*. Primary batteries are intended for single use and are typically recycled or discarded after depletion. Secondary batteries, commonly called rechargeable batteries, are designed to be recharged after discharge. Recharging is accomplished by applying an electrical current to the electrodes and reversing the direction of electron flow (Linden et al., 2019). Battery-powered vessels, EVs, and electric micromobility devices use high-capacity secondary (rechargeable) batteries.

### 2.2 Lithium-ion Batteries

LIBs use lithium compounds in the anode and cathode, as well as the battery electrolyte. Secondary LIBs dominate the vehicle and vessel electrification markets due to high specific energy, energy density, and specific power properties (Dahn & Ehrlich, 2019). Of the seven maritime battery types currently in use, 99% (by quantity) are classified as LIBs (Table 1). As such, this paper will limit discussion to secondary (rechargeable) LIBs.

Table 1. Battery distribution across the worldwide battery-powered fleet (DNV, 2025).

Battery Type	Distribution
Lithium nickel manganese cobalt oxide (NMC)	79%
Lithium iron phosphate (LFP)	12%
Lithium titanate oxide (LTO)	5%
Lithium nickel cobalt aluminum oxide (NCA)	3%
Nickel cadmium (Ni-Cd)	0.5%
Lead acid	0.4%
Lithium nickel cobalt manganese aluminum oxide (NCMA)	0.1%

LIB electrolyte is typically composed of a lithium salt and a solvent. Many electrolyte formulations are proprietary and not readily disclosed by the manufacturer. The most prominent commercially used lithium salt in electrolyte is lithium hexafluorophosphate ( $\text{LiPF}_6$ ), though other lithium-based salts are being explored for specific battery applications (Dahn & Ehrlich, 2019). Similarly, a wide variety of solvents are available for use in LIBs. These solvents may be used alone or blended to achieve the desired battery performance characteristics (Dahn & Ehrlich, 2019) (Table 2).

Table 2. LIB electrolyte solvents (Dahn & Ehrlich, 2019).

Common LIB Electrolyte Solvents
Ethylene carbonate (EC)
Propylene carbonate (PC)
Dimethyl carbonate (DMC)
Ethyl methyl carbonate (EMC)
Diethyl carbonate (DEC)
Fluoroethylene carbonate (FEC)
Methyl acetate (MA)
Methyl propionate (MP)



### 2.2.1 Thermal Runaway

Lithium-ion cells can go into *thermal runaway* when an internal, exothermic chemical reaction begins generating heat faster than the cell can cool. Thermal runaway may be an immediate or delayed result from physical, electrical or thermal abuse, errors in the manufacturing process, or aging (Koch S., 2019; Di Matteo, 2023). High-capacity batteries are physically larger and store more energy than standard consumer device (e.g., mobile phone, laptop computer) batteries, but at the cost of external cooling efficiency. The reduced surface area-to-volume ratio results in greater temperature differences within the battery and when combined with increased stored energy, makes these batteries more susceptible to thermal runaway than smaller, consumer device batteries (Feng et al., 2014; Wei & Li, 2024).

The rate of a chemical reaction increases with temperature (Encyclopaedia Britannica, 2025). As the cell temperature increases, the rate of the chemical reaction increases, creating a feedback loop. In lithium-ion cells, this may result in rapid self-heating that can quickly propagate to surrounding cells (Koch S., 2019). At the onset of thermal runaway, cell temperatures can rise at a rate of up to 1.8°F (1°C) per second until reaching 248°F to 320°F (120°C to 160°C), when the separator melts and fails. The separator's failure creates an internal short circuit and nearly instantaneous battery discharge, causing an exponential increase in internal cell temperature. Rapidly decomposing electrolyte and expanding electrolyte gas may vent from or burst the battery casing and result in subsequent fire and/or explosion (Koch, 2019; Wei et al., 2023). Studies have recorded internal cell temperatures during thermal runaway exceeding 1800°F (982°C) (Yuan et al., 2020). To date, the only proven method of disrupting the thermal runaway feedback loop is by venting or removing heat from the battery. Removing heat energy reduces internal cell temperatures below the thermal runaway onset temperature, interrupting the self-sustaining thermochemical reaction (Koch S., 2019).

### 2.3 Summary

- **LIBs contain hazardous and combustible materials including toxic metals and solvents.**
- **Thermal runaway is a thermochemical reaction feedback loop resulting in rapid and uncontrolled self-heating of the battery.**

## 3 LITHIUM-ION BATTERY FIRE HAZARDS

### 3.1 Fire

Many factors affect the combustion behavior of a battery cell including cell chemistry, state of charge (SOC), battery shape, etc. (Ponchaut et al., 2015; Chen et al., 2017; Yuan et al., 2020; Ghiji et al., 2021). Fire responders will likely not have immediate access to this information. The hazards discussed below are typical of high-capacity LIB fire scenarios involving maritime and electric vehicle batteries, and electric micromobility devices.

LIB fires may include jet flames, flying debris from explosion, electrical arcing, and sparking (Wang et al., 2012). Rapidly escaping combustible vapors generated from decomposing electrolyte may produce sporadic jet flames reaching 2732°F (1500°C) (Ping et al., 2015). Several battery types including lithium nickel



manganese cobalt oxide (NMC) produce oxygen during thermal runaway, supporting combustion (Zhong et al., 2019; Jo et al., 2024).

### 3.2 Gas and Particulate Generation

The gas generated during LIB thermal runaway is often called vent gas or thermal runaway effluent gas (TREG) (Sauer et al., 2024). The volume of gas generated from a LIB fire is estimated to be 2 to 3 liters (0.035 to 0.07 cubic feet) per amp-hour (Ah) of installed battery capacity (Koch S. , 2019). The total power available on a battery-powered vessel is often measured in kilowatt-hours (kWh) because it accounts for the battery system voltage (V). The relationship between Ah and kWh is described by the following expression (Equation 1):

$$\frac{(kW)(1000)}{V} = Ah \quad (1)$$

For example, an average battery-powered ferry with a 1050 kWh system (DNV, 2025) and bus voltage of 720 V has 1458 Ah of installed capacity (Equation 2).

$$\frac{(1050 \text{ kWh})(1000)}{720 \text{ V}} = 1458 \text{ Ah} \quad (2)$$

In this case, thermal runaway involving the entire battery system can produce 2916 to 4373 liters (103 to 154 cubic feet) of TREG. The installed capacity on battery-powered vessels varies by vessel type, operation, and power application. The 2024 average installed capacity for a variety of battery-powered vessels is displayed in Figure 3.

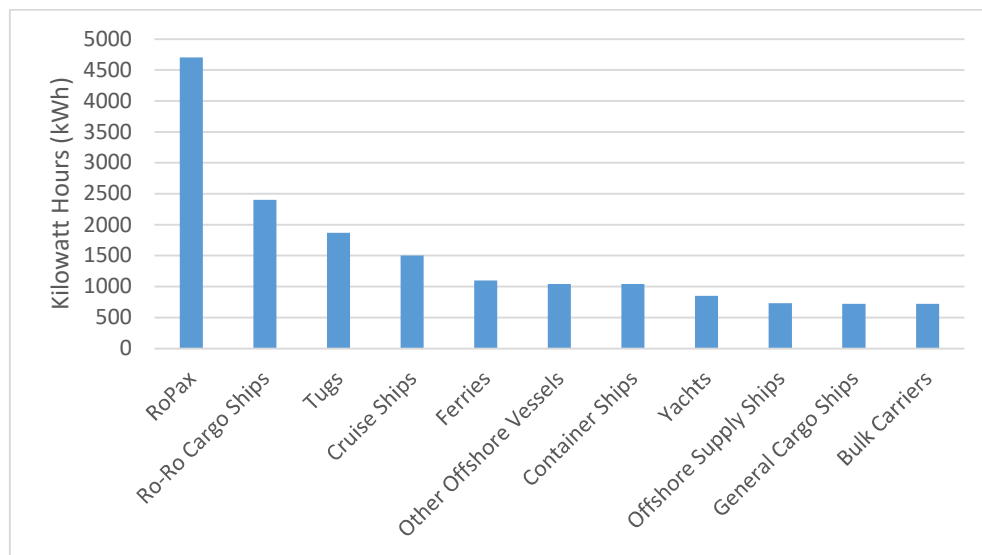


Figure 3. Average 2024 installed battery capacity (kWh) by battery-powered vessel type (DNV, 2025).

#### 3.2.1 Combustible Gas and Explosion Potential

The amount of combustible gas generated during LIB self-heating and thermal runaway varies by battery chemistry and SOC (Golubkov et al., 2014; Koch et al., 2018; Zhong et al., 2019). Koch et al. (2018) found

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NMC batteries with electrolyte composed of  $\text{LiPF}_6$  salt and mixtures of EC, EMC, and DMC solvents produced hydrogen ( $\text{H}_2$ ), methane ( $\text{CH}_4$ ), ethane ( $\text{C}_2\text{H}_6$ ), propane ( $\text{C}_3\text{H}_8$ ), ethene ( $\text{C}_2\text{H}_4$ ), and propene ( $\text{C}_3\text{H}_6$ ) during self-heating and thermal runaway. Of the total TREG collected, approximately 35%, was composed of combustible gases (Koch et al., 2018).

In an enclosed space, combustible gas concentrations may cause an explosion if ignited (Zhong, 2019). Combustible gas ignition creates a volumetric expansion of 5 to 8 times, resulting in a pressure increase of 72 to 116 pounds per square inch (5 to 8 bar) (Larsson, 2017). Explosion in an enclosed compartment not equipped with an adequate pressure relief system may result in over pressurization or in extreme cases, bursting (Maritime Battery Forum, 2025). A recent study found the combustible gas volume released during thermal runaway of a large battery-powered tool (e.g., electric lawnmower) or electric micromobility device battery was adequate to partially or completely eject the garage door from a modern construction two car garage (Sauer et al., 2024). If the concentration of combustible gas in the space is above the upper explosive limit, a delayed explosion may occur from air exchange and dilution once the space is accessed or ventilated (NOAA, 2025).

### 3.2.2 Toxic Gas

Koch et al. (2018) found that toxic gases comprised approximately 65% of the TREG collected from a NMC battery. Toxic gases including carbon dioxide ( $\text{CO}_2$ ), carbon monoxide ( $\text{CO}$ ), hydrogen fluoride ( $\text{HF}$ ), and phosphorous oxyfluoride ( $\text{POF}_3$ ) are commonly found in LIB TREG (Andersson et al., 2016; Larsson, 2017; Koch et al., 2018; Qiu et al., 2023; Ubaldi & Russo, 2024). Concentrations of  $\text{HF}$  and  $\text{CO}$  were found to exceed the National Institute for Occupational Safety and Health's *Immediately Dangerous to Life or Health* values regardless of battery chemistry (Ubaldi & Russo, 2024).

Numerous other toxic gases may be produced during the thermal runaway chemical reaction and, like combustible gas generation, are dependent on battery chemistry, SOC, and combustion conditions (Golubkov et al., 2014; Zhong et al., 2019). Examples of other toxic gases found in TREG include hydrogen cyanide ( $\text{HCN}$ ), hydrochloric acid ( $\text{HCL}$ ), hydrogen sulfide ( $\text{H}_2\text{S}$ ), sulfur dioxide ( $\text{SO}_2$ ), and formaldehyde ( $\text{CH}_2\text{O}$ ) (Diaz et al., 2019). Additionally, vapors and aerosols from LIB electrolyte solvents including DMC, DEC, and EC have been observed during LIB fires (Ubaldi & Russo, 2024).

### 3.2.3 Particulates

Many particulates generated during combustion become airborne and are carried by TREG. LIB fires produce particulate matter 2.5 microns ( $\text{PM}_{2.5}$ ) and smaller composed of black carbon, metals, ions, and polycyclic aromatic hydrocarbons (Held et al., 2022; Claassen et al., 2024; Premnath et al., 2024). Metals including aluminum, cobalt, copper, lithium, manganese, and nickel were detected in NCA battery TREG, and aluminum, copper, iron, and lithium in LFP battery TREG (Ubaldi & Russo, 2024). Heavy metal-oxides of nickel, manganese, and cobalt were found in the soot of EV fires from NMC batteries (Held et al., 2022). Various ions including fluoride and chloride were detected in airborne particles and soot from NMC and LFP battery fires (Held et al., 2022; Claassen et al., 2024). Premnath et al. (2024) noted high levels of ultrafine particulates (smaller than 100 nanometers) which are more easily able to enter through the respiratory system and into the blood and organs, though analysis wasn't conducted to determine the composition of those particles.



### 3.3 Summary

- **LIB fires can occur quickly and may produce flames exceeding 2700°F. Fire may be accompanied by explosion and flying debris, jet flames, arcing, and sparking.**
- **A significant volume of combustible gas, toxic gas, and inhalable hazardous material particulates is released during a LIB fire.**
- **If ignited, combustible gas in an enclosed compartment may explode and result in over pressurization or bursting.**
- **Explosion may also occur when accessing enclosed spaces.**

## 4 LITHIUM-ION BATTERY FIRE SUPPRESSION

The tremendous heat energy, sporadic jet flames, and ongoing chemical reactions make extinguishing LIB fires extremely challenging. Large amounts of water, water spray, or foam are recommended to suppress or extinguish LIB fires (NOAA CAMEO, 2025; ABS, 2022; IMO SSE, 2020). Existing gaseous and dry powder extinguishing agents have been tested with varying results, but both lack adequate cooling properties to slow chemical reactions and limit thermal propagation to adjacent cells, which allows cells to reignite (Russoa et al., 2018; Sun et al., 2021; Yuan et al., 2021; ABS, 2022).

### 4.1 Water and Foam

Water has been found to be the most effective (and abundant) suppression agent due to its ability to provide cooling and extinguish electrolyte-based flames, though a significant amount of water is required (Russoa et al., 2018; Diaz et al., 2020; Ghiji et al., 2020; NTSB, 2020; Pertsev, 2022). The National Fire Protection Association recommends a 33% increase in sprinkler water density to suppress potential EV fires in parking structures (O'Connor, 2022). Pressure water mist was effective for suppression and cooling in EV battery fire testing, as was low-expansion foam to a lesser degree (IMO SSE, 2020). It should be noted that water and foams are conductive and may increase the possibility of electrocution as well as damaging (e.g., short circuiting) unaffected cells (Pertsev, 2022; Di Matteo, 2023). Furthermore, previous studies have identified increased HF gas generation when water was applied to LIB fires due to interaction with electrolyte salts ( $\text{LiPF}_6$ ) (Larsson, 2017; Zhang et al., 2021).

### 4.2 Commercially Available Lithium-ion Battery Fire Suppression Agents<sup>3</sup>

Commercial fire suppression agents marketed for LIB fires may be effective on small battery fires or for initial response to large capacity battery fires; however, RDC has not had the opportunity to evaluate these products. Two prevalent agent types are aqueous vermiculite dispersion (AVD) and F-500 Encapsulator Agent (EA). AVD uses water and chemically exfoliated vermiculite, a mineral resembling mica composed of magnesium-aluminum-iron silicate (EPA, 2025) that is marketed to provide cooling and establish an

<sup>3</sup> Discussion of specific products does not infer USCG Type Approval, USCG acceptance, or endorsement.





oxygen barrier through formation of a vermiculite film (AVD Fire Limited, 2025; Kanex Fire Solutions Limited, 2025; LiCELL Fire Protection, 2025). F-500 EA is a water dispersed surfactant containing fatty alkyl ethers reaction products with aliphatic acids, linear aliphatic alcohols, and nitrilotrisethanol aliphatic soap (Pane et al., 2015; Schwenk et al., 2024). The manufacturer purports F-500 EA is effective because it addresses all legs of the fire tetrahedron (i.e., heat, oxygen, fuel, and chemical chain reaction) (HCT, 2025).

A third agent class is potassium-based aerosols. Like potassium-based dry powders but with finer particles, these aerosols interrupt the combustion process by bonding to oxygen and hydrogen free radicals, but do not provide cooling (AF-X Fireblocker, 2025; RSL Fire, 2025; Stat-X, 2025). While many aerosol systems are fixed installations, some are offered in handheld or grenade-style delivery systems.

### 4.3 Commercially Available Lithium-ion Battery Fire Fighting Equipment

High pressure cutting extinguishers advertise reduced water use and fire suppression time by penetrating battery casings or modules and circulating cooling water around the cells (Cold Cut Systems Svenska AB, 2025; Fognail, 2025), but require a dedicated pump unit. Fire blankets designed for LIB fires are marketed to protect surroundings by isolating flames and jet fires until fire suppression equipment is on-scene (Bridgehill, 2025; CellBlock Fire Containment Systems, 2025; Li-Fire Suppression Solutions, 2025). Fire blankets may be useful for small consumer devices (e.g., laptop computers), and for initial shipboard response to electric micromobility devices and EVs if the surrounding area is accessible and tenable. However, fire blankets may prevent overhead sprinkler water from reaching the fire and could accelerate thermal runaway by containing heat energy and should not be considered a sole extinguishing solution.

### 4.4 Summary

- **Water and foams are most effective at suppressing and extinguishing LIB fires.**
- **Commercial extinguishing agents marketed for LIB fires may lack the cooling capacity required to interrupt thermal runaway.**
- **LIB fire blankets may benefit initial response by isolating the fire from surroundings, but could impede overhead sprinkler and deluge system cooling water.**

## 5 LITHIUM-ION BATTERY POST-FIRE HAZARDS

### 5.1 Battery Monitoring

Delayed thermal runaway has been observed in batteries subjected to physical, thermal, or electrical abuse. Internal, localized failures within the batteries can increase the possibility of a future fire or thermal runaway incident (Liu et al., 2020). LIBs may reignite weeks after the fire has been extinguished (NOAA CAMEO, 2025; SAE International, 2019). Fire-affected batteries should be monitored for swelling or bulging; electrolyte leakage; noises such as gurgling, bubbling, crackling, hissing or popping; white smoke; arcs and sparks; and temperature increase (NOAA CAMEO, 2025; SAE International, 2019). Electrolyte



has been described as having a sweet, ether-like odor (SAE International, 2019). A thermal camera or infrared temperature probe is recommended for monitoring battery temperature (NOAA CAMEO, 2025; SAE International, 2019). Batteries should be removed and disposed of by a fire response organization (e.g., shoreside fire responders, HAZMAT units, licensed contractors).

### 5.2 Fire Scene and Equipment Contamination

As discussed in Sections 3.2.2 and 3.2.3, LIB fires generate toxic gas and particulates. Studies have found these substances in spaces post-fire, and on personal protective equipment exposed to LIB fire smoke, exceed safe exposure levels (Held et al., 2022; Szmytko et al., 2022). In tests evaluating firefighter's protective clothing (i.e., turnout gear) left in an enclosed space during a LIB fire, formaldehyde levels exceeded the acceptable level for contact with skin<sup>4</sup> by 12 times; cobalt by 24 times; and polycyclic aromatic hydrocarbons by 67 times. Lithium, organic phosphoric acid compounds, and oligomer cyclic compounds were also found in substantial quantities (Szmytko et al., 2022). Many domestic fire departments have implemented LIB fire decontamination procedures for personal protective equipment including carbon dioxide dry cleaning and other advanced methods to reduce contact exposure risks (Hoey, 2025). Additionally, water runoff from NMC battery fires were found to contain cathode metals such as nickel, manganese, cobalt, lithium and aluminum, as well as electrolyte-based organic carbonates such as EC and EMC (Bordes et al., 2024).

### 5.3 Summary

- **LIBs may reignite up to weeks after a fire and must be monitored until removed and properly disposed.**
- **HAZMAT particulates and residues will contaminate any material exposed to smoke including firefighting water.**

## 6 RECOMMENDATIONS

Unique fire, explosion, toxicity, and HAZMAT exposure risks may be present during battery fires and in post-fire scenes. Large quantities of combustible and toxic gas, as well as hazardous particulates, are produced in a LIB fire. Traditional shipboard responses to conventional ICE fuels or structural fires may not suffice for LIB fires. The material composition of battery electrodes, electrolyte, and battery containment can produce intense rapidly evolving, fires with little forewarning. Shipboard crews and fire response teams, USCG search and rescue units, and USCG Sector response and prevention personnel must be cognizant of the hazards unique to LIB fires during both fire response and post-fire operations.

RDC offers the following recommendations:

- **Personnel with the potential to encounter or respond to LIB fires should familiarize themselves with the hazards discussed in this document.**

<sup>4</sup> Per OEKO-TEX STANDARD 100, Supplement PPE & Materials for PPE



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While commercial hybrid and full electric vessel crews should receive specialty fire response training from their vessel classification society or battery system vendor/integrator, vessels transporting LIBs in the form of EVs and micromobility devices may not have the same opportunity. Documents such as *Best Practices for the Transport of Electric Vehicles On Board Vessels* (ABS, 2022) and the USCG Sector Southeastern New England white paper *Mitigating Risk during the Maritime Transportation, Handling, and Stowage of Electric Vehicles* (Brewer, 2023) provide insight for practical fire mitigation and response strategies. Periodic LIB fire response drills involving local fire departments are also encouraged.

➤ **Search and rescue personnel should be aware of LIB fire-specific hazards.**

USCG units should be advised if a fire involves a LIB prior to arriving on-scene. Tactics for affected underway vessels may require modification from standard procedures such as avoiding a downwind approach to minimize toxic gas and HAZMAT exposure risks.

➤ **Use adequate PPE post-fire to mitigate contact and inhalation exposure risk.**

Vessel crew and USCG Sector prevention personnel (e.g., marine investigators and marine inspectors) must understand residual HAZMAT risks when attending the vessel for a casualty investigation and damage assessment. Particulate matter will be deposited on surfaces, and ultrafine particles may become airborne by personnel moving about the space. Standing firefighting water could contain toxic metals and organic carbonates such as EC, EMC, and DMC. PPE should be treated as contaminated once worn.





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