ATF Fire Research Laboratory
Technical Bulletin

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Best Practices for the Safe Handling of Lithium Cells and Batteries

Introduction

The purpose of this Technical Bulletin is to provide guidance for the safe handling of lithium cells and batteries (lithium-ion and lithium metal). Guidance on the safe handling of battery-powered tools and equipment is also offered. Members of law enforcement, the fire service, the fire investigation community, forensic service providers, evidence collection and storage technicians, and others have the potential to encounter damaged lithium cells and batteries during their work and may also use battery powered equipment to perform their work.

Typical cell geometries include cylindrical, prismatic, pouch, and coin or button types (Figure 1).

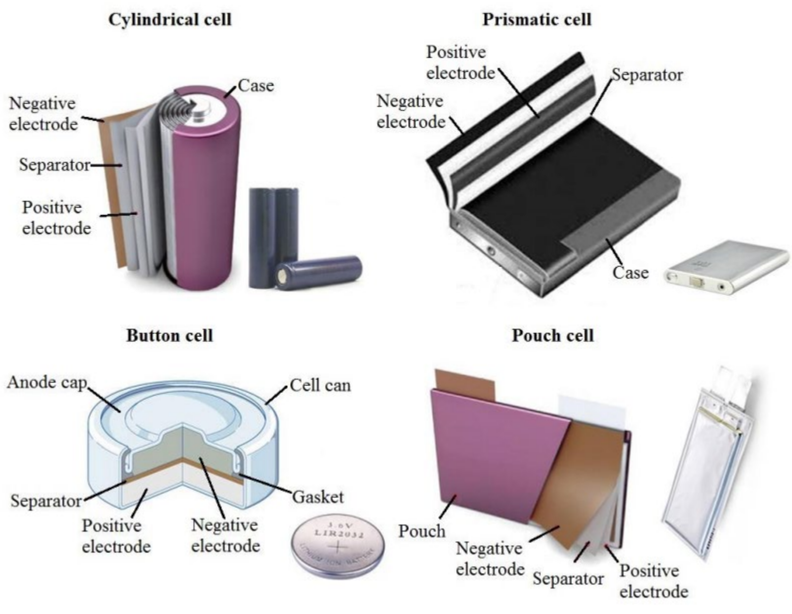

Figure 1 – Typical lithium cell geometries, including cylindrical (top, left), prismatic (top right), button (bottom left), and pouch (bottom right) [1].

Electronic devices can be powered by a single lithium cell, or by several cells connected to form a battery pack or module. These can include:

- Everyday devices such as cellular phones, flashlights, electronic cigarettes, power tool batteries, portable radios, tablet style computers, and laptop computers.

- Mobility devices such as e-scooters and e-bikes.

- Battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs) and hybrid electric vehicles (HEVs).

- Energy storage systems such as portable battery packs, residential energy storage systems, and commercial or utility-scale energy storage systems.

The safe handling of damaged cells and batteries fire suppression, the scene investigation, collection, transport, storage, and laboratory examination is important to minimize the risk of re-ignition and exposure to chemical hazards. Furthermore, failures of undamaged tools, electronics, and other equipment can be avoided with a few simple practices.

Problem Statement

Lithium cells and batteries are designed to operate under specific conditions and environments. When cells and batteries are used outside of these conditions, failures can occur, resulting in the cell or battery overheating, over-pressurizing, venting or rupturing.

Thermal runaway in a lithium cell or battery is characterized by uncontrollable self-heating and can result in the production of combustible and toxic gases, smoke and fire, and possible ejection of particulates or shrapnel [2]. During thermal runaway, materials used in the construction of the cell or battery can reach their ignition temperature or be ignited by arcing/sparking of the cell components. The failure can ignite other combustible items in the immediate area of the cell or battery, or remotely due to the ejection of flaming material. Thermal runaway in a single cell within a battery pack can cause cascading failures of adjacent cells. Thermal runaway within a battery pack can result in the ejection of cells from the pack, leading to fires remote from the pack's original location.

Failures of lithium cells and batteries can be caused by electrical, mechanical, or thermal abuse, as well as poor design or maintenance, and manufacturing defects. For example:

- Electrical abuse can be caused by charging or discharging a battery or cell at a rate beyond design specifications, overcharging (e.g., using an inappropriate charging device), or over-discharging.

- Mechanical abuse includes physical damage, which can be caused by dropping, crushing, penetrations or impacts.

- Thermal abuse can be due to using, storing, charging, or discharging in an environment outside design specifications. Exposure to a fire environment may also be considered thermal abuse and may result in cell or battery failure.

- Manufacturing defects include foreign objects introduced during the manufacturing process, component defects (e.g., anode, cathode, or separator inhomogeneities), or other component or assembly defects that may allow internal short circuits or failures of the cell assembly.

Failures can be delayed by minutes, hours, days, or months as the cell or battery continues to break down internally after the initial damaging event. The failure can occur during routine use, while charging, or during storage.

Batteries can fail directly or indirectly. Direct failure may be a cell or battery failing due to abuse or defect. Indirect failures can be caused by an adjacent cell failing in a battery pack or exposure to an external fire.

Fire Suppression Considerations and Post-Suppression Stabilization

Steps must be taken to prevent further damage and re-ignition of damaged cells and batteries.

Personal protective equipment (PPE) should be used when handling damaged lithium cells and batteries. Failed cells and batteries can produce chemical compounds that are hazardous to health and the environment. Minimum PPE should include protective eyewear, exam gloves (e.g., nitrile or latex), and a protective outer garment (e.g., lab coat, protective coveralls, Tyvek suit, etc.). Caution is necessary when using metallic tools during overhaul or scene processing, as these could further damage cells or batteries or create a short circuit, resulting in a failure.

Damaged cells or batteries and extinguishing agent run off may also be contaminated. Precautions against cross contamination and coordination with hazardous materials teams and federal, state, or local environmental protection organizations may be necessary.

The stability of cells or a battery post-fire or explosion can vary depending on the degree of damage. A cell or battery that has been fully discharged with all available fuel consumed will be more stable than those with less damage. An enclosure may limit or prevent the introduction of a suppression agent to the battery of a device, limiting the cooling necessary to prevent cascading thermal runaway within a battery assembly. It's also important to remember that cells or batteries that are thought to be "dead" can still contain enough energy to cause a significant thermal event.

Sustained cooling may be needed to prevent re-ignition or cascading thermal runaway. Water may be the most effective agent for cooling lithium cells and batteries in the field, limiting failure of adjacent cells of a battery pack or module. Continued monitoring post-fire with a thermal imaging camera or similar device may be used to ensure that thermal runaway does not continue. The time required for this monitoring will depend on the size of the battery and the extent of the damage to the battery. Insufficient monitoring, resulting in a lack of cooling, can lead to re-ignition later. A cell or battery that has been cooled may still fail at a later time.

Fire/Explosion Scene Investigation Considerations

Considering the prevalence of lithium-ion and lithium metal cells and batteries in consumer electronics, an investigator is likely to find numerous devices at fire/explosion scenes. While it is possible that a lithium cell or battery initiated the fire or explosion, it is also possible that the devices were merely damaged by the event. The damage caused by the event may make these devices more susceptible to failure, potentially leading to thermal runaway. Therefore, care must be taken when examining a fire or explosion scene to avoid further damage to these items.

Fire and explosion scenes are inherently dangerous, requiring appropriate PPE and safety considerations. For guidance on PPE selection and use, and other safety considerations, review the IAAI's *Fire Investigation Health and Safety Best Practices* [3]. As stated previously, minimum PPE when handling fire damaged cells and batteries should consist of protective eyewear, exam gloves, and an outer garment.

Cells and batteries that have failed independently of, or because of a fire or explosion have the potential to be displaced from their original locations. If the investigator encounters a battery-powered device, it is important that they recover as many cells as possible to account for all potential evidence. The investigator should determine how many cells were present within a device or battery pack, which will likely begin with determining the device manufacturer and the battery or cell ratings (voltage, and capacity or amp-hour rating).

For example, typical lithium-ion batteries have a nominal cell voltage of 3.6 V, and a peak voltage of 4.2 V when fully charged. An 18 V battery pack would need five cells connected in series to obtain the desired voltage:

$$\frac{18\, V\ battery\ pack}{3.6\, V\ per\ cell} = 5\ Cells$$

For marketing purposes, manufacturers may use a different voltage level to specify their pack voltage. For example, Milwaukee uses five cells rated nominally 3.6 V to obtain their 18V battery pack rating. However, DeWalt batteries also use five cells, but use the fully charged 4.2 V cell rating to specify a 20 V battery pack rating. However, if the voltage of a fully charged battery from each manufacturer was measured, they would both measure approximately 20 V [4].

The capacity, or amp-hour (Ah) rating, of a battery pack can be increased to a limited degree by using cells with a higher capacity. To increase the capacity further, multiple arrays of cells are connected in parallel. Batteries may use a combination of series and parallel cell connections to create a battery with increased voltage and capacity. For example, a 2 Ah Milwaukee 12 V battery pack has three cells, but a higher capacity 4 Ah pack has six cells (Figure 2).

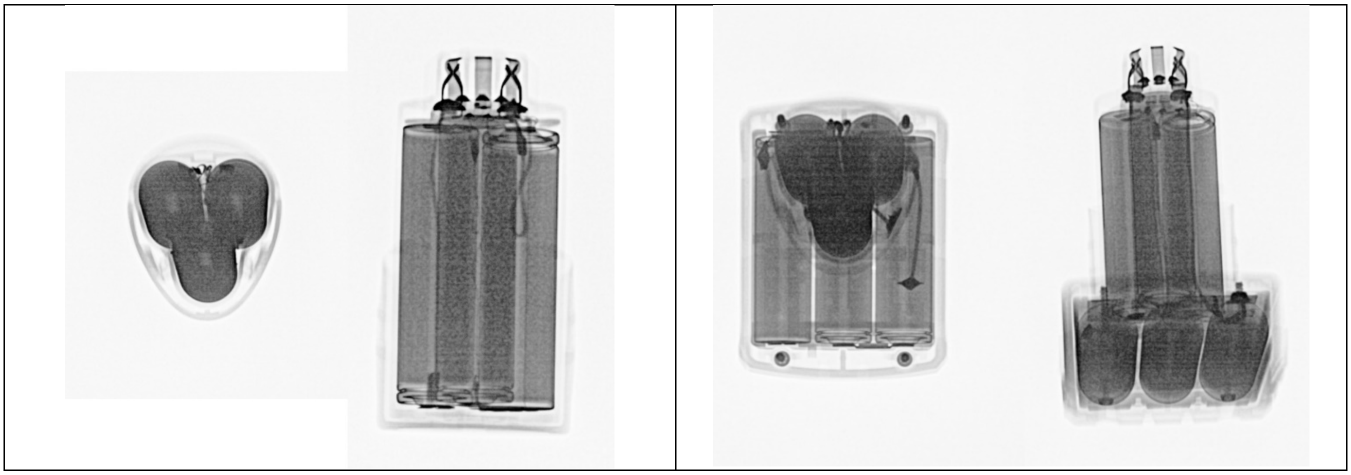

Figure 2 – Radiographic (x-ray) images of 12 V Milwaukee battery packs. A 2 Ah pack with three cells is shown on the left (top and front views), and a 4 Ah pack with six cells is shown on the right (top and front views).

Extreme care should be used when handling cells and batteries on a scene. The investigator should avoid work practices that would further damage a cell or battery or cause a short circuit, both of which could cause thermal runaway and subsequent fires or explosions. Furthermore, to prevent additional damage that can result in re-ignition and to preserve the items for future examination, disassembly of cells and battery packs on scene should be avoided.

If the investigative team has determined that there is no need to collect any cells or batteries as evidence, consideration should be given to the handling and storage of the items to be left at the scene. The cells or batteries that have been damaged by the fire may still contain energy and can therefore go into thermal runaway. After documenting the locations and conditions of any artifacts, the investigator may want to consider bagging any individual cells or batteries to prevent accidental shorting. Furthermore, it may be prudent to isolate the artifacts in a safe area within the scene so that if a failure does occur during or after the investigation, the failure occurs in an area where further damage or fire spread would be limited.

For example, the artifacts could be individually bagged and then placed in a noncombustible container (e.g., ammunition can, evidence can, oven or microwave) within the scene. Bagging would help to isolate conductive components and placing the bagged items in a noncombustible container would help to contain any failures that may occur after leaving the scene. Note that if a damaged cell or battery off-gases within a sealed container, there may be an associated pressure rise within that container. The container may need to be vented or capable of withstanding an associated pressure increase. The individual bags should be labeled as to where the artifacts originated, and all items and activities should be documented thoroughly. It is also important to communicate the locations and condition of these items to subsequent investigators.

Packaging, Transportation, and Storage

Damaged lithium cells and batteries are classified as a hazardous material and therefore several regulations restrict their transportation by land, sea, and air. Applicable regulations are provided by:

- United States Code of Federal Regulations (CFR)
- Department of Transportation (DOT)
- Federal Aviation Administration (FAA)
- International Maritime Organization (IMO)
- United Nations (UN)

Packaging, storage, and transportation should employ means and methods to minimize potential re-ignition and fire spread should ignition occur. Consideration should be given to isolating exposed connections with non-conductive materials and securing switches and connections or terminals to prevent accidental activation, discharge, or short circuiting. Proper packaging at the scene will help to reduce the potential for failure or thermal runway while in transit or storage.

Section 173.185 of the United States Code of Federal Regulations details the requirements for the transportation of lithium cells and batteries [5]. Lithium cells and batteries collected from the scene of a fire or explosion would fall under the requirements of *damaged, defective, or recalled (DDR) products* (Title 49 CFR 173.185 Section F). In summary, the requirements for the handling of lithium cells or batteries collected from the scene of the fire or explosion are:

- Place each cell or battery in its own individual, non-metallic package that completely encloses the cell or battery.
- The inner packaging must be surrounded by an absorbent, electrically non-conductive, and non-combustible cushioning material. Examples include sand, cat litter, vermiculite, and commercial products designed specifically for the shipping of lithium batteries and cells.
- The outer shipping container must meet the requirements of the U.S. Code of Federal Regulations. Ideally, this container would protect the contents inside from further damage and would also contain any failure of its contents should one occur. Cardboard boxes are not an appropriate outer container.
- The shipping container must be labeled with letters that are at least 12 mm (0.47 in.) high with the following "Damaged/defective lithium-ion battery" and/or "Damaged/defective lithium metal battery" as appropriate.
- The shipping container must also be marked with the lithium battery mark (Figure 3) of the specified size and color. Labels with this mark are available at major shipping retailers. The label must have a red border and have dimensions of 4 inches by 4 inches (10 cm by 10 cm). Some exceptions are allowed for small packages.

Figure 3 - Mark required for shipping of lithium cells and batteries.

- The appropriate UN code must replace "UN ####" in the lithium battery mark. These codes are:
  - UN3480 for lithium-ion cells or batteries
  - UN3481 for lithium-ion cells or batteries contained in or packed with equipment
  - UN3090 for lithium metal cells or batteries
  - UN3091 for lithium metal cells or batteries contained in or packed with equipment
  - If a package contains more than one type of product, all appropriate UN numbers must be placed in the battery mark.

For safety reasons, damaged, defective, or recalled lithium cells and batteries must be transported by highway, rail, or vessel only. They **MUST NOT** be transported by air.

Commercial products and kits are available for the shipment of lithium cells and batteries.

When storing lithium cells and batteries as evidence from a fire or explosion scene, consideration should be given to the potential for failure or thermal runaway. Evidence containing lithium cells and batteries should be stored separately from other evidence or within an enclosure specifically designed for the storage of lithium cells and batteries. Commercial products for the storage of lithium cells and batteries are available.

Safely discharging a cell or battery in a controlled manner may also be considered prior to long-term storage of evidence. More guidance on the discharging of these items can be found in the Disposal section of this document. However, consideration should first be given to whether this process could adversely affect the subsequent examination of the artifacts. For example, submerging a lithium cell or battery in a saltwater brine solution will likely cause corrosion of some components.

Disposal

Disposal of lithium cells and batteries is regulated by federal, state, and local regulations. Lithium products should not be placed in the general waste stream. Commercial products and services exist for the disposal of lithium cells and batteries.

Discharging a damaged cell or battery of stored energy prior to disposal will reduce the risks of fire after disposal. Submerging a cell or battery in a solution of baking soda and water may be used to safely discharge the cell or battery, while minimizing the corrosion of the components. This solution should contain at least 78 grams of baking soda per liter of water [6]. The size of the container and volume of solution should be scaled based on the size of the battery or cell. Alternatively, the electrodes alone can be submerged in the solution to limit corrosion of the cell or battery components and contamination of the solution. Ultrasonic agitation has also been shown to shorten the discharge time and reduce the propensity for corrosion [7].

Use, Storage, and Charging of Battery-Powered Tools and Equipment

Lithium-ion batteries have a limited range of ambient temperatures that they should be exposed to during charging or discharging. In cold environments, a battery should be brought to room temperature before charging or use. Metal dendrites can form inside a cold battery when charged, which is irreversible. Each repeated charging cycle of a cold battery can make the dendrites larger, making the battery more susceptible to an internal short circuit if it is later damaged. Conversely, charging a battery produces heat, so charging in an already hot environment can exceed the temperature rating of the battery, leading to a failure or thermal runaway.

It is also advisable to not let a fully discharged battery sit for a prolonged time. All lithium-ion cells have an inherent impedance and will continue to self-discharge over time. If a fully discharged battery is allowed to sit for too long, it can become over-discharged, which can irreversibly damage the battery.

Best practices for the use of lithium-ion battery-powered tools and equipment include:

- Do not charge a cold battery; bring it up to room temperature for several hours first.
- Do not charge a hot battery or charge the battery in an elevated-temperature environment.
- Do not charge a battery immediately after being fully discharged; give the battery time to cool off.
- Do not let a fully discharged battery to sit for a prolonged period.
- Purchase cells, batteries, and battery powered products from reputable sources and ensure the cells, batteries, or products meet applicable product standards. This can be verified by third-party certification markings such as UL, ETL, CSA, etc.
- Use chargers that come with the product/battery or a charger that meets the voltage and current specifications of the product.
- Consider removing cells or batteries or products with built-in batteries from your vehicle when parked in hot or cold environments.
- Immediately remove a swollen or damaged battery from service and dispose of in an approved manner.

References

[1] K. Murashko, *Thermal modelling of commercial lithium-ion batteries,* Lappeenranta University of Technology, 2016, p. Pg. 32.

[2] UL Research Institutes, "What is Thermal Runaway?," 24 August 2021. [Online]. Available: https://ul.org/research/electrochemical-safety/getting-started-electrochemical-safety/what-thermal-runaway. [Accessed 24 June 2024].

[3] International Association of Arson Investigators Health and Safety Committee, "Fire Investigator Health and Safety Best Practices," International Association of Arson Investigators, 2022.

[4] Ask This Old House, "YouTube: Battery Voltages - Tool Lab - Ask This Old House," 29 March 2022. [Online]. Available: https://www.youtube.com/watch?v=321Kc28H4b0. [Accessed 1 August 2024].

[5] United States Code of Federal Regulations, "Title 49 Subtitle B Chapter I Subchapter C Part 173 Lithium Cells and Batteries," [Online]. Available: https://www.ecfr.gov/current/title-49/subtitle-B/chapter-I/subchapter-C/part-173/subpart-E/section-173.185. [Accessed 7 June 2024].

[6] A. D. S. Jones, P. G. Courtney and G. Sutter, "Investigation of Electrically Conductive Aqueous Solutions for De-Energizing Lithium-Ion Batteries," UL Solutions, 2023.

[7] M. Torabian, M. Jafari and A. Bazargan, "Discharge of Lithium-Ion Batteries in Salt Solutions for Safer Storage, Transport, and Resource Recovery," *Waste Management and Research,* vol. 40, no. 4, pp. 402-409, 2022.

Additional Resources

49 CFR § 173.185 - Lithium cells and batteries.
https://www.ecfr.gov/current/title-49/subtitle-B/chapter-I/subchapter-C/part-173/subpart-E/section-173.185

NFPA: Lithium-Ion Battery Safety
https://www.nfpa.org/education-and-research/home-fire-safety/lithium-ion-batteries

UL FSRI: The Science of Fire and Explosion Hazards from Lithium-Ion Batteries
https://fsri.org/lithium-ion-battery-guide

U.S. Department of Transportation Pipeline and Hazardous Materials Safety Administration: Transporting Lithium Batteries
https://www.phmsa.dot.gov/lithiumbatteries

U.S. Environmental Protection Agency: Lithium-Ion Battery Recycling
https://www.epa.gov/hw/lithium-ion-battery-recycling