WHEN ENERGY IGNITES

Exploring Thermal Runaway Failure Modes in Lithium-ion Batteries

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Stop. Look around. You might notice a laptop, mobile phone, tablet, wristwatch, power tool, digital camera, landscape lighting, electric bike, lawn mower, vehicle, or any number of battery-operated products. Some of these products, like flashlights, wristwatches or remote controls, house primary batteries such as alkaline AA/AAA or lithium-metal coin cells that cannot be recharged. Some of these products contain secondary batteries such as lithium-ion, nickel-cadmium, nickel-metal hydride, or lead-acid that can be recharged and reused, making them (more specifically, lithium-ion batteries) the more desirable option for powering our everyday products. The increased use of these lithium-ion batteries in wide-ranging applications brings an increased focus on battery safety. More specifically, the focus turns to battery or battery-operated products that can lead to potentially catastrophic results if failure occurs, such as explosion or fire, that can result in significant property loss or even loss of life. By understanding how a battery works, along with common failure modes and mitigation systems, the industry can be better prepared to act if these incidents do occur.

HOW DO LITHIUM-ION BATTERIES WORK?

A quick look at Fig. 1 below will illustrate the ins and outs of how a battery works. A typical commercial lithium-ion battery (LIB) is composed of a negative electrode (anode) made from carbon/graphite coated onto a copper current collector, a transition metal oxide positive electrode (cathode) coated onto an aluminum current collector, a separator, and an electrolyte composed of lithium salt in an organic solvent. When the battery is in use, lithium ions (Li^+) move through the electrolyte from the anode to the cathode, as illustrated below. Chemical reactions occur that generate electrons and convert stored chemical energy in the battery to electrical energy. When the battery is charging, the chemical reactions go in reverse.

LIB cells are available in different form factors such as cylindrical, coin, pouch, or prismatic. At the high level, Fig. 2 explains a typical LIB cell-to-module-to-pack assembly in a bottom-up approach.

LIB FAILURE

Lithium-ion batteries can experience a non-energetic failure, such as battery capacity loss or swelling, or an energetic failure, such as thermal runaway, which is what will be focused on here. Thermal runaway (Fig. 3) events and ensuing fires and explosions are the primary cause of catastrophic LIB failure.

There are a number of ways in which LIB thermal runaway can be triggered, which include thermal abuse, mechanical abuse, electrical abuse, latent defect, or an internal short circuit. Misuse of the LIB product/battery can lead to one or more of these conditions. The exact effects that occur during thermal runaway are dependent on several key factors, including, but not limited to, the specific makeup of the battery itself, battery state of charge (amount of charge relative to the battery capacity), health, etc. When the LIB cell experiences one of the abuse conditions, a chain reaction is initiated at a critical onset temperature leading to increased heat and temperatures. Cell thermal runaway can spread to neighboring cells, additional components within the battery module, pack, or system, resulting in smoke, flame, fire, and/or an explosion.

An electric vehicle collides with a secondary vehicle. In this scenario, a mechanical abuse condition can occur when an external object crushes or punctures/penetrates the battery. If this should happen and a cell separator is torn in the process, it can lead to an internal short-circuit and, in turn, rapid heating of the cell and can trigger thermal runaway. This is why it's very important for electric vehicle crashes to be handled with additional precautions, as there are many first responders who arrive on the scene when an accident takes place. Mechanical abuse can also happen when shipping and handling packages of cells, battery packs, or equipment containing packs. These items can be dropped, crushed, and punctured, causing mechanical damage to the cells.

When was the last time you borrowed someone's charger to charge your phone or another portable lithium-ion battery-powered device? Using an incorrect or non-manufacturer recommended charger can lead to overcharge, an example of an electrical abuse condition. Electrical abuse and mechanical abuse can lead to internal short-circuit resulting in heat generation, a thermal abuse condition. Electrical abuse conditions like fast charging, over-discharging, and external short-circuit can lead to a thermal runaway event. At the cell level, charging at high rates, high state of charge, or at low temperatures can lead to lithium plating, the deposition of metallic lithium on the anode graphite surface. In severe cases, lithium plating forms needle-like deposits that penetrate the separator, causes internal short, and inevitably, can lead to thermal runaway. Over-charge can also significantly degrade the cathode owing to excess removal of lithium that can add to an unstable structure and thermal runaway result. Faulty packaging or careless handling of the cells can lead to an external short-circuit, which can produce large amounts of current, rapidly generate heat, and can lead to thermal runaway.

Aside from mechanical, thermal, or electrical abuse, a latent defect, like a contaminant introduced during the battery cell manufacturing process, is another factor that can trigger a thermal runaway event with explosion, fire and/or smoke. These defects can take place at any step of the manufacturing process, including but not limited to, in cell raw materials, electrode coatings, contaminants introduced during assembly processes, misplaced, misaligned, or damaged components, manufacturing-induced electrode damage (scratches, punctures, tears, active material displacement), electrode tab burrs, weld spatter, etc.

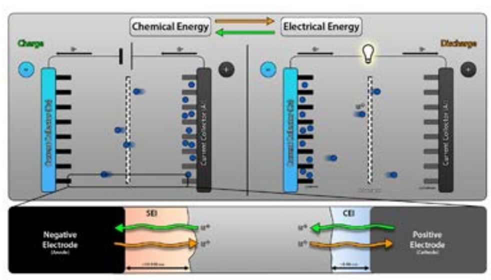

FIG. 1 Lithium-ion battery (LIB) operating principle with focus on solid electrolyte interphase (SEI) at the negative electrode (anode) surface and cathode electrolyte interphase (CEI) at the positive electrode (cathode) surface.

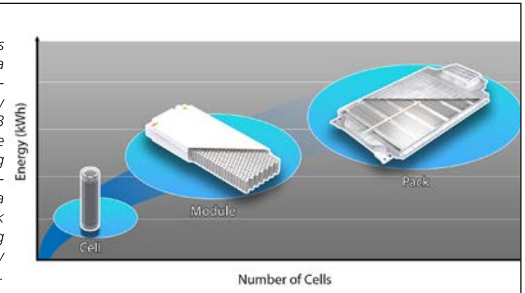

FIG. 2 This figure shows a cylindrical lithium-ion battery (LIB) cell, a LIB battery module assembled using several cylindrical cells, and a LIB battery pack assembled using several battery modules.

FIG. 3 Lithium-ion battery (LIB) thermal runaway overview.

LIB RISK MITIGATION

While several causes (as described in the above section) can potentially lead to lithium-ion battery (LIB) thermal runaway failure, certain mitigation strategies can be implemented prior to, during, or after a thermal event to help reduce the risk of a potential fire or explosion.

At the cell level, lithium-ion battery cell enclosures can be designed to have safe venting. In case the cell's internal pressure rapidly increases, this can help prevent pressure build-up, which, if left unchecked, can potentially lead to violent venting, ignition of vent gases, and/or ejection of cell contents. Similarly, an optimal venting strategy is important at the LIB pack level. At the LIB pack or system level, a battery management system (BMS) is one of the most critical safeguards. A robust BMS continuously monitors cell, module, and pack characteristics and works alongside the battery thermal management system to maintain optimal temperatures throughout the pack. A BMS's active control strategy, for example, in electric vehicles, keeps the battery within the safe temperature, voltage, and current operational limits, in addition to providing information related to the battery. The BMS can protect the battery by alerting the user in case the battery experiences undesirable conditions such as over or under charge, discharge, temperature, etc., and subsequently performing appropriate trip or protective actions.

Test and validation that meets applicable safety standards and regulations at the cell, module, pack, or system level can help reduce the risk of potential field incidents. Product safety, certification, standards, or regulatory organization examples include United Nations, International Electrotechnical Commission, Society of Automotive Engineers, Underwriters Laboratories, and the International Organization for Standardization, to name a few.

CONCLUSION

The use of rechargeable lithium-ion batteries in our everyday products is here to stay for the foreseeable future, and in turn, so is the potential risk of fire or explosion from a thermal runaway event initiated by LIB abuse, latent defect or other contributing factors. As we charge into the future, a better understanding of how these batteries operate and fail can meaningfully help mitigate the risk of a (thermal) event occurring. This knowledge will also enable us to maintain the investigative strategies and knowledge to identify the cause when it does.

Sanket Kadam is a battery consultant and the Energy Storage Practice Group Lead at S-E-A. He earned his bachelor's in chemical engineering from the Institute of Chemical Technology, along with his master's in chemical engineering from Michigan State University. His experience consists of roles in battery research, agile battery technology, and automotive electric vehicle startups. His experience includes engineering, materials, and test-driven battery cell-to-module-to-pack safety profile improvement, product development process, electric vehicle builds, commissioning, and launch activities, cell, module, and pack level testing, design of experiments, design verification plan and report activities.