Battery Failure Analysis and Characterization of Failure Types
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October 8, 2021

This article is an introduction to lithium-ion battery types, types of failures, and the forensic methods and techniques used to investigate origin and cause to identify failure mechanisms. This is the first article in a six-part series. To read other articles in this series, click here.

Renewable and sustainable forms of energy have seen a steady increase in share of overall electric power generation and use over the past 10 years driven primarily by concerns of climate change, as well as oil price uncertainty and resource availability. The intermittency problem of some of these energy types has been largely offset, but not entirely solved, by the use of battery energy storage systems (BESS). Specifically, lithium-ion (Li-ion) batteries, which have been the most common type of battery used in BESS, offer many advantages including smaller size, power density, and energy density to name a few. The price per kWh of Li-ion batteries has also seen a sharp decrease over the past 10 years, which has contributed to making energy costs for these renewables more affordable, and continued technologic advancements have improved Li-ion battery performance. These batteries are a versatile and highly scalable energy storage medium that can take on many shapes and chemistries, enabling their use in a variety of applications. However, like any other technology, Li-ion batteries can and do fail. It is important to understand battery failures and failure mechanisms, and how they are caused or can be triggered. This article discusses common types of Li-ion battery failure with a greater focus on thermal runaway, which is a particularly dangerous and hazardous failure mode. Forensic methods and techniques that can be used to characterize battery failures will also be discussed.

Battery cells can fail in several ways resulting from abusive operation, physical damage, or cell design, material, or manufacturing defects to name a few. Li-ion batteries deteriorate over time from charge/discharge cycling, resulting in a drop in the cell’s ability to hold a charge. For Li-ion batteries, when the cell’s capacity drops below a certain percentage of its nominal capacity, i.e., generally 80% but can be as low as 60%, the battery will fail to operate. Charging and discharging a cell at too high of a C rate, which is measurement of current supplied by or to the battery during charge and discharge, e.g., a battery with a rated capacity of 1,000 mAh discharged at 1C can supply 1 Amp for 1 hr, can shorten the life of the battery and may result in other failure mechanisms. Physical damage from an impact or drop can result in internal damage to the cell. Electrolyte vapor production and leak out of the jellyroll may lead to swelling. A cell that is improperly sealed or that is susceptible to a loss of sealing can result in the electrolyte leaking out, and potential interior exposure to external oxygen. This may result in an explosion if the battery has any level of charge since a lithiated carbon anode is highly reactive to atmosphere. Some combination of these conditions, including abusive operating conditions, can result in a thermal runaway failure. This article focuses on the causes related to thermal runaway failures.

Thermal runaway is a dangerous type of failure that can result in an explosion and fire. In larger scale Li-ion BESS, this failure can be cascading and catastrophic, since thermal runaway is heat driven. One cell failing in this manner can quickly cause the heat of the resulting fire to spread to other surrounding cells and trigger the same failure. The results can pose a serious threat not only to property, but also poses a
severe health hazard to people since thermal runaway can result in both fire and the production of toxic gases. An example of a similar failure occurred in Moorabool, near Geelong, on July 30th of this year: “Two Tesla Megapacks were engulfed in flames when a fire broke out during initial testing at a Victorian Big Battery site,” which spread to nearby batteries.\(^1\) According to the article, the “...‘most likely’ cause of the fire [was thought] to be a coolant leak in the Megapack cooling system, which caused a short circuit that led to a fire in an electronic component. The resulting heating then led to a thermal runaway and fire that spread to a second battery... Energy Safe Victoria (ESV) said several changes had since been made to prevent any future fires, including each Megapack cooling system being inspected for leaks before on-site testing, and the introduction of a new ‘battery module isolation loss’ alarm to firmware.” A photograph showing this failure is shown in Figure 1 below. This naturally poses the following question: what is thermal runaway and why does it occur?

![Figure 1: Photograph of Moorabool thermal runaway fire](image)

Thermal runaway is a process in which an uncontrolled chain of exothermic reactions produce heat and continually cause an increase in battery temperature. As cell temperature increases, these reactions and other degradative processes occurring internally produce an even greater amount of heat, resulting in an uncontrollable rise in temperature. Depending on the stability and other characteristics of a Li-ion battery’s cathode, oxygen can be liberated during this process. Oxygen, which is naturally contained in the battery’s cathode, can then react with compounds in the battery cell such as hydrocarbons in the electrolyte, which can cause a fire and/or explosion at high temperatures. There is a threshold temperature to initiate these exothermic chain reactions, and even highly localized heating can trigger this event. For example, internal short circuiting within the cell produced by contact made between the electrodes can result in a sufficient heating and temperature increase. Physical impacts to the cell can trigger localized heating as well.

\(^1\) [https://www.abc.net.au/news/2021-09-28/fire-at-tesla-giant-battery-project-near-geelong-investigation/100496688](https://www.abc.net.au/news/2021-09-28/fire-at-tesla-giant-battery-project-near-geelong-investigation/100496688)
All Li-ion batteries are susceptible to this type of failure, but their thermal stability and thermal runaway temperature is tied strongly to the cell’s cathode chemistry. Li-ion batteries are often referred to by their chemistry, which is dictated by the cathode chemistry. Lithium iron phosphate (LFP) and lithium cobalt oxide (LCO), are two examples. The bonding characteristics and chemical structure of the cathode makes the battery more or less chemically and thermally stable, with LFP type batteries being far more stable than LCO type batteries. These different chemistries result in different physical crystal structures that encompass the cathode, which strongly controls cell stability and how fast a particular battery can be charged and discharged safely. These crystal structures also affect Li-ion mobility or how quickly and efficiently they can be inserted during intercalation (charging/discharging). For example, LCO batteries have higher nominal voltages giving them a higher energy density, but the layered structure of the cathode can limit the mobility of the Li-ions making it more dangerous to force higher charge/discharge rates. Conversely, lithium manganese oxide (LMO) batteries have 3-dimensional spinel structures that enhance intercalation, allowing these cells to charge and discharge safely at higher rates. Forcing high charge/discharge rates puts stress on the battery electrodes and can also result in heating, which can lead to thermal runaway. For this reason, consideration of the cell cathode chemistry is an important factor when determining a particular application, as improper operation of the battery can lead to a thermal runaway event.

If a thermal runaway failure occurs, it is often important to determine why the event happened. This could be important to operators to potentially prevent a future event, for insurance and potential litigation, and for reporting to regulatory agencies. A fast response and taking measures to preserve the site and potential evidence or artifacts of interest are essential to ensure an accurate origin and cause investigation can be thoroughly performed. As part of the investigative effort, data review, e.g., SCADA, collecting information, reviewing any available footage, and collecting drone footage using infrared thermography, can all be methods used to aid in heat mapping to identify the origin or probable origins. If an approximate origin is identified, or multiple probable origins are identified, collection of evidence, establishing chain of custody, and further laboratory analysis would be prudent. Using the correct methods and analytical techniques will help to identify the failure mechanisms involved, and combined with other obtained information, a methodical approach using causal mapping can help to identify one or multiple causes or contributing factors to the event, and to establish a timeline and sequence of events.

Examination and analysis of physical evidence obtained from the scene is typically conducted in a forensic laboratory, such as BakerRisk’s Forensic Materials Engineering Laboratory. Methodical photo-documentation of the as-received condition of collected evidence, and documentation of the process of destructive testing activities, are essential activities. The following are useful examination methods for assessing collected evidence:

- **Non-destructive examination:** aside from visual examination and low magnification optical microscopy, one useful tool would be computed tomography (CT) scanning of modules or cells. Prior to any opening, removal, or sectioning of the evidence, imaging of the interior acquired via non-destructive means can be useful prior to proceeding with destructive activities.

- **Microscopic examination:** using data previously collected non-destructively can aid in subsequent destructive activities. Opening of a cell using a glove box and sectioning of cells to reveal the interior of a cell, including the jellyroll, is a necessary step to better understand a cell’s construction. Evaluation of cross-sections allows for assessing the quality of spot welds and measuring spacing and distances. Examples of this type of analysis are shown in Figure 2, which was collected by BakerRisk in our materials and testing laboratory for a button cell Li-ion battery.
(LCO) from a portable electronic device. Evaluation of artifacts of interest at high magnification using scanning electron microscopy (SEM) can be useful when examining the condition of the electrodes, and in combination with SEM, using energy dispersive x-ray spectroscopy (EDS) enables semi-quantitative chemical analysis of debris and assesses general cathode elements.

Figure 2: Example of a cell opening (left) of a button cell Li-ion battery, and metallographic cross-section (right) of battery

- Chemical analysis and structural characterization: verifying the cell chemistry is a necessary step. Determining, in general, what elements are present can be completed using EDS. X-ray diffraction (XRD) can provide insight into the cathode crystal structure. Nuclear magnetic resonance (NMR) spectroscopy has been a very valuable technique for evaluating cell chemistry and other chemical and electrochemical characteristics.

- Electrochemistry: electrochemical impedance spectroscopy (EIS) is a useful tool that can provide data on electrode dynamics and allows for comparison of cells. Often, inferences can be made with regard to electrochemical properties of the cells. NMR has also shown great promise in evaluating electrochemical parameters in batteries during charge/discharge, provided the cell is compatible with NMR.

- Exemplar comparison: evaluation and data collection from exemplar modules and cells can be useful for baseline comparisons to subject modules and cells. This can also be in the form of collecting charge/discharge curves, cyclic voltammetry, and assessing capacity. An example of charge/discharge cycling and product testing of a LFP battery conducted by BakerRisk is shown in Figure 3 below.
Using the above techniques, in combination with proper information gathering, can allow a forensic investigator to identify failure mechanisms as well as origin and cause or causes of the event. Knowledge of relevant technical documents, including UL 1642, UL 2054, UL 1973, UL 9540, and relevant on-going work in this industry including IEC 62619 and IEC 62620 is also essential. These techniques can be applied to the assessment and evaluation of the other failure mechanisms discussed in the above sections. To understand the risk of such events, it is important to understand the likelihood of failure, which is the focus of the second article in this six-part series.