THERMAL RUNAWAY IN LI-ION BATTERIES – INITIATION & SAFETY STRATEGIES

Sneha Lele
Managing Engineer
Exponent
Phoenix, AZ

Abstract

Single cell field failures, especially in large battery systems require consideration of how these failures can impact neighboring cells and subsequently the entire system. Inducing worst-case thermal runaway in Lithium-ion (Li-ion) cells is an effective way of evaluating the consequences of single cell failures. Methods of inducing thermal runaway include the use of heaters, nail penetration, overcharge, dent/pinch tests, etc. Each method has its own advantages and disadvantages when it comes to implementation and effectiveness in causing thermal runaway. Implementation becomes more challenging as the scale of the battery system increases.

This paper presents a landscape of the different methods of inducing thermal runaway in single cells within larger battery systems. In this paper we also discuss other aspects that need to be considered when designing a battery system to lower the risk of a single cell failure propagating to the entire battery system.

Introduction

Technological advancements and rapidly increasing manufacturing capacities with reduced costs have resulted in a steep increase in popularity of Lithium-ion (Li-ion) batteries for grid storage applications. The current market for grid-scale battery storage both in the US and globally is starting to be dominated by Li-ion chemistries. Since the widespread adoption of Li-ion batteries for grid storage applications, several incidents have raised safety concerns with the batteries. This has given rise to a need to better understand the propagation of a single cell failure in the battery. To prevent propagation, battery systems must be designed with redundant protection features. In the absence of a commonly accepted methodology to evaluate propagation of a single cell thermal runaway in a large battery system, a UL 1973 Internal Task Group was set up in 2016. This has resulted in the induction of the 'Tolerance to internal cell failure' tests in Edition 2 of UL 1973-2018 (Standard for Batteries for Use in Stationary, Vehicle Auxiliary Power and Light Electric Rail (LER) Applications). The intent of this test is to evaluate system tolerance by simulating thermal runaway in a single cell using techniques that emulate real-life occurrences in the field as closely as possible.

This paper will provide an overview of Li-ion battery systems, some of the causes and effects of field failures, UL standard 1973 and the tolerance to internal cell failure tests described in the standard. The paper will also provide an overview of techniques commonly used to initiate thermal runaway in Li-ion cells.

Li-ion batteries and field failures

In recent years, there have been several reported fires at grid connected Li-ion battery energy storage facilities in the US, Japan and South Korea. These incidents have resulted in several mandatory safety regulations for these battery systems. Large battery systems where hundreds of Li-ion cells are connected together can result in the release of a large amount of energy if a single cell failure propagates to other cells in the battery system. The cause of Li-ion cell failures in the field is a well-researched topic. The consequences of a Li-ion cell failure can range from a cell that cannot be charged or discharged to a cell that may go into thermal runaway. Thermal runaway occurs when the thermal stability threshold of the cell chemistry is exceeded, and the cell releases its internal energy very rapidly causing self-sustaining exothermic reactions. Figure 1 illustrates some of the causes and failure modes of Li-ion cells.

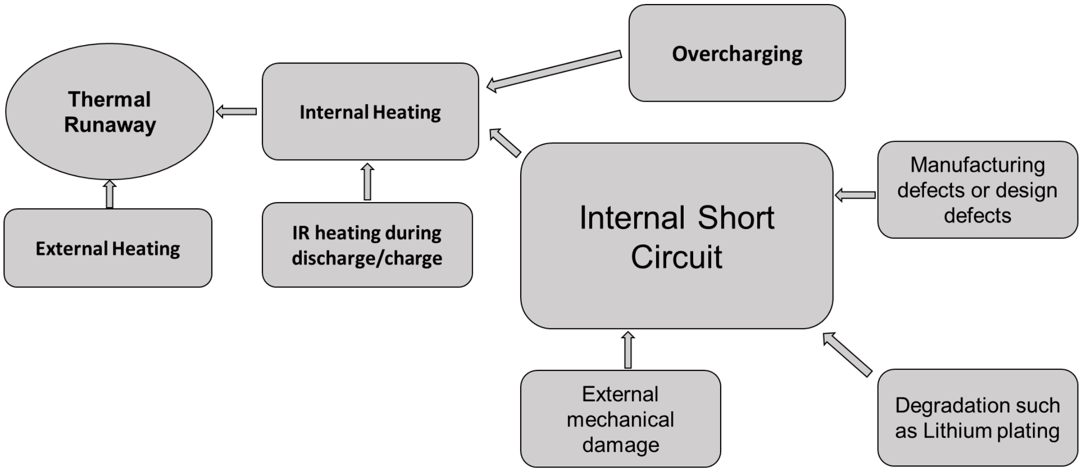

Figure 1 Failure Modes in Li-ion Cells

Thermal runaway reactions can occur with any type of cell irrespective of the chemistry, including lead acid and nickel cadmium. These reactions are particularly concerning with Li-ion cells as cells with this chemistry have a higher energy density than most other chemistries, usually contain a flammable electrolyte and are tightly packed to make higher capacity battery packs [1]. However, thermal runaway in cells of any chemistry can pose a substantial risk. The thermal runaway behavior of single Li-ion cells is well researched and documented. Some of the effects of such a behavior include venting of gases, high temperatures, ejection of internal cell contents and sometimes self-ignition of cells [2]. Internal short circuit which is basically an uninterrupted and unintended charge flow between the cathode and anode in these cells is one of the more common failure modes that can result in exothermic behavior. Failure of a single cell in itself may have little impact on a large battery module but may be sufficient to cause a cascading thermal event. A cell failure can cause enough heat generation to result in a chain reaction which in a worst-case scenario can consume the entire battery system [2].

Li-ion batteries used in large battery systems are typically designed with integrated safety mechanisms for external electrical abusive scenarios such as overcharge or overcurrent. There are many safety standards and test protocols that list a variety of tests to validate the effectiveness of these safety mechanisms. However, these safety schemes are unable to alleviate internal fault conditions such as an internal short circuit [3]. Most Li-ion battery safety standards do not address methods to test a battery for an internal cell short circuit condition and the resulting propagation of failure. To this effect committees such as UL and IEC have recently incorporated specific specialized testing that recommend testing to address propagation of failure within battery systems.

UL 1973 - Standard for Batteries for Use in Stationary, Vehicle Auxiliary Power and Light Electric Rail (LER) Applications

UL 1973 [4] is one such standard that includes a section for ‘tolerance to internal cell failure’ tests. Single cell failure simulation testing is not designed to determine if a single cell will undergo a thermal runaway reaction due to any specific cause. Rather, the purpose of this testing is to assume that a single cell within a larger battery system will undergo thermal runaway due to an unidentified cause, and to then determine if that reaction will pose a safety threat to the users and surrounding environment [1].

The intent of this standard is to enable a Li-ion battery system to be designed to mitigate a single cell failure leading to a thermal runaway of that cell. The possible cell failure mechanisms can vary widely depending on the application and operating conditions of battery systems. Hence the standard recommends choosing a failure mechanism that closely replicates a realistic stress situation. It also recommends determining the cell location considered to fail, such that it has the highest potential to lead to an external hazard, taking into consideration the cell’s proximity to other cells and materials that may lead to potential for propagation [4].

Some of the other published literature that incorporates similar test recommendations applicable for stationary applications include:

- IEC 62619 (2017) Safety requirements for Secondary Lithium Cells and Batteries, for use in Industrial Applications, Sect.7.3 “Considerations for internal short-circuit – Design evaluation”
- NASA JSC 20793 Rev D (2017) “Crewed Space Vehicle Battery Safety Requirements”, Sect. 5.1.5, “Thermal Runaway Propagation”
- SANDIA REPORT SAND2017-6925, “Recommended Practices for Abuse Testing Rechargeable Energy Storage Systems (RESSs)”, July 2017, Sect. 3.4. “Failure Propagation Test”

UL 1973 provides some recommended methods for simulating cell internal short-circuits. This list, although not exhaustive, is representative of some of the known methods utilized for this testing.

1. Internal cell failure through internal defects which entails special construction of the chosen cell:
    a. Introduction of conductive contaminant
    b. Reproduction of separator defects such as holes or tears
    c. Installation of an internal heating element
2. Internal cell failure through application of external stress:
    a. External heater application
    b. External indentation without enclosure penetration
    c. Nail penetration through cell casing
    d. Single cell short circuit (for cells that do not contain internal protection devices such as PTC (positive temperature coefficient) or fuse)
    e. Single cell overcharge (for cells that do not contain internal protection devices such as PTC or fuse)

Some of these methods will be discussed in the following sections with examples.

Single Cell Failure Techniques

Some of the recent incidents that involved thermal runaway events that have eventually consumed entire battery systems and/or caused loss of property and personnel have been linked to internal flaws in a single cell within the battery system [4]. The degree of damage caused by a single cell failure depends on a range of factors such as the ambient conditions, quality of the cell, cell chemistry, etc. Based on these factors and the standards mentioned in the previous section, several ways can be implemented to simulate single cell failures and to study the outcomes in these different conditions.

Although these different techniques are representative of the many ways that a cell can fail, they basically are intended to test the thermal stability limits of the cell. Thermal runaway, which is the result of exceeding this limit, causes rapid internal heating within the cell which is essentially due to the breaking down of the separator and a direct exothermic reaction between the anode and the cathode. Figure 2 shows the different stages of a cell undergoing thermal runaway.

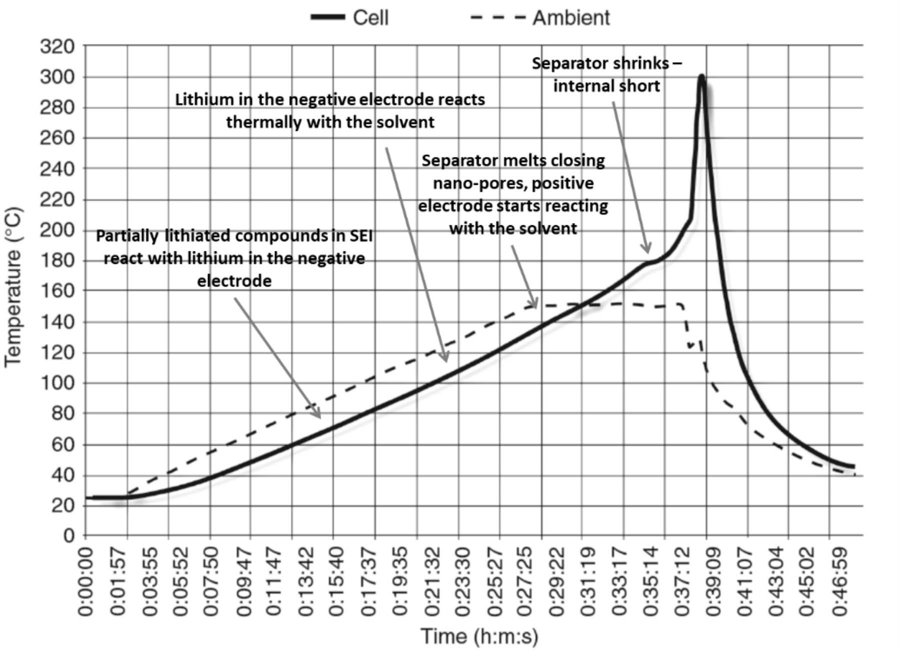

Figure 2 Thermal Runaway of a Li-ion Cell [5]

For Li-ion cells, thermal runaway can be caused by a variety of reasons such as thermal abuse, mechanical abuse, poor manufacturing practices, electrical misuse or cell construction issues. Hence the single cell failure techniques can be classified into three general categories:

1. Thermally induced
2. Mechanically induced
3. Electrically induced

Thermal Techniques

The most straight-forward way to thermally destabilize a Li-ion cell is to subject it to external heating. This method is widely used by testing facilities as it does not require any special modification to the cell and can be generally easily implemented. As the thermal behavior of a Li-ion cell is well known for a specific chemistry, this method offers almost a fool-proof way of inducing a failure. Depending on the size and form of the Li-ion cell and based on the possible failure scenario in a given application, this heat exposure can be achieved in a number of ways:

- Externally powered heaters – most suitable for flat cells to ensure maximum thermal coupling
- Nichrome wire – most suitable for cylindrical cells or oddly shaped cells
- Laser heating – localized heating using lasers causing damage in a specific area

Figure 3 shows one such setup using an external powered heater to precondition the Li-ion cell and eventually heat it to failure. As the temperature raised over approximately 200°C, the cell voltage dropped to zero and the cell went into thermal runaway. Figure 4 shows the temperature profile obtained using thermocouples on the cell, with temperatures reaching upwards of 1300°C during the thermal event.

Figure 3 Thermal Technique using Externally Powered Heaters

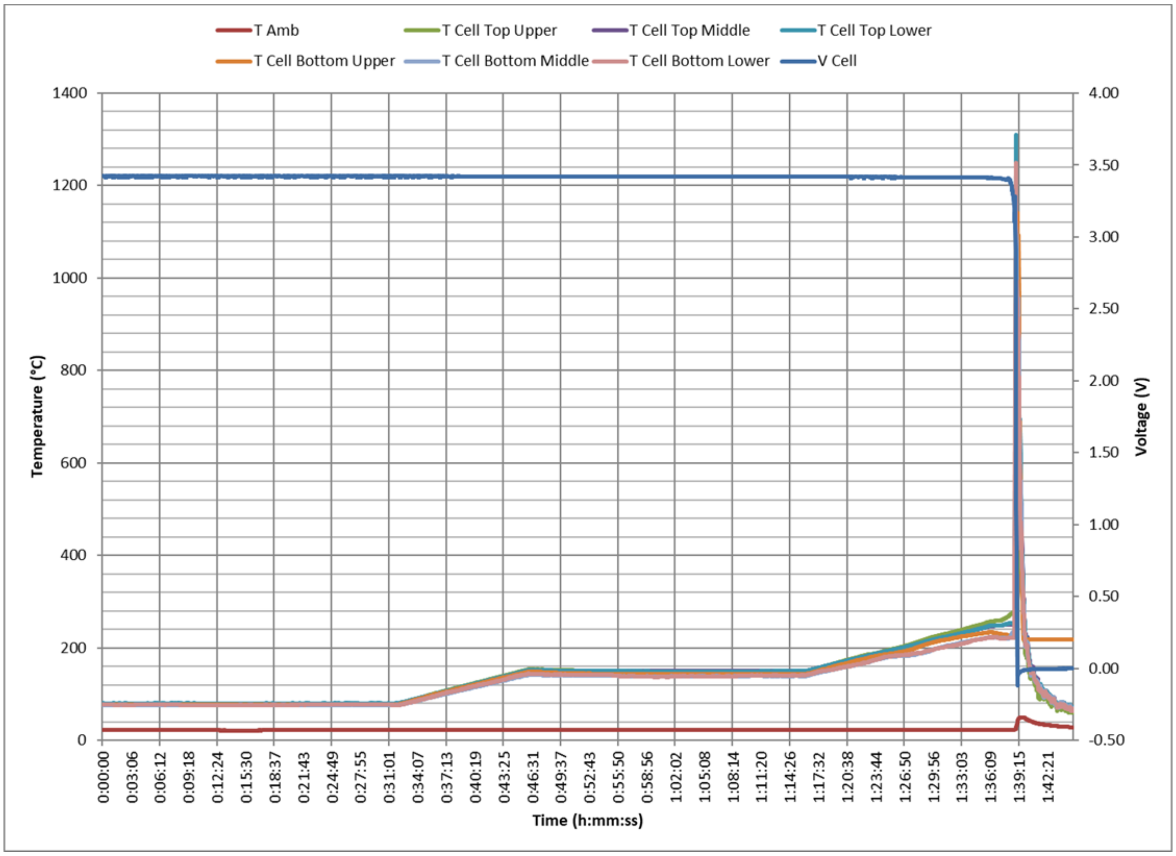

Figure 4 Thermal Runaway in Li-ion Cell Under Test

Mechanical Techniques

Mechanical techniques provide a fast and efficient way of inducing failure. These methods typically require an involved test setup and vary greatly depending on the type of cell (e.g., pouch or cylindrical). Some of the methods recommended in literature are:

- Nail penetration – used widely for pouch, cylindrical and prismatic cells
- Pinch/dent test – mostly suitable for pouch cells
- Blunt object crush test – used for pouch and cylindrical cells but rarely used for hard case prismatic cells.

Figure 5 and Figure 6 are two examples of mechanical techniques applied to test a cell and the post-test results.

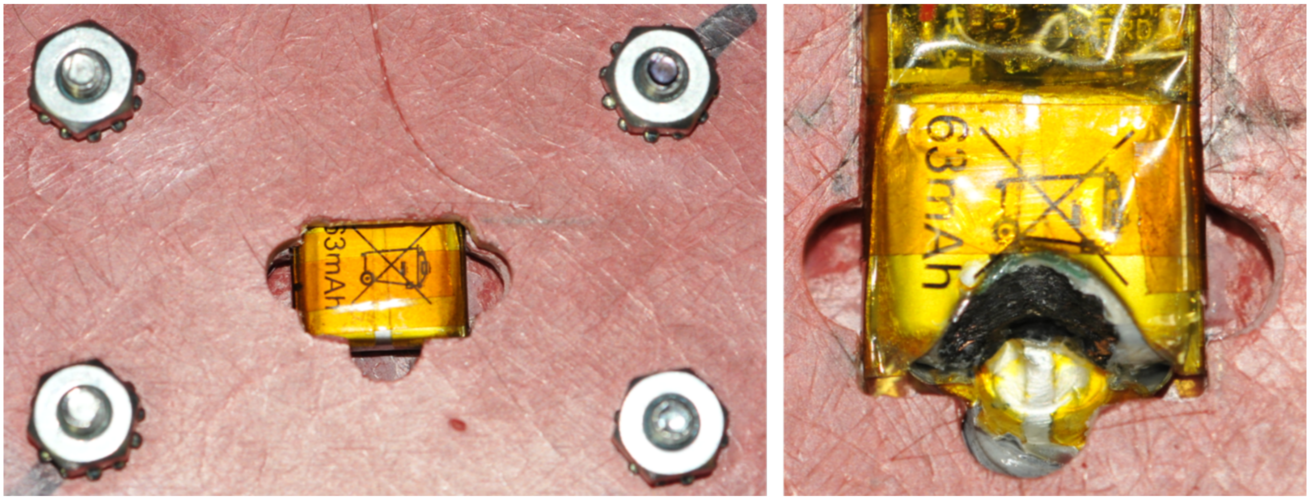

Figure 5 Pinch Test Fixture for Pouch Cell & Post-test Result

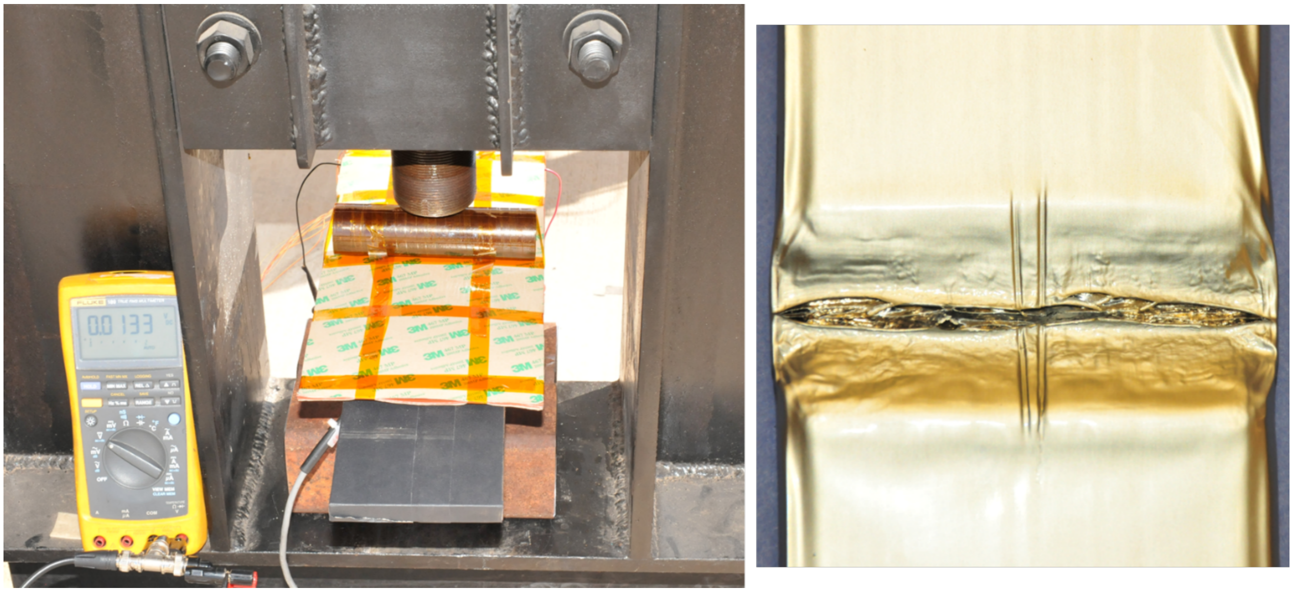

Figure 6 Blunt Rod Crush Test

Although these methods provide a faster way to induce thermal runaway, the outcomes are heavily influenced by the cell structure and mechanical properties of the separator. Additionally, the results are influenced by the test method and properties such as force applied, nail/rod surface, shape, material and the speed by which a mechanical force is applied.

Electrical Techniques

Electrical techniques have been traditionally used to induce failures in a cell. These methods again are highly dependent on the type of cell being tested and may not be suitable for certain cells that include an in-built current interrupt device (CID) or a PTC. Nevertheless, these techniques can still be used for cells that have external fuses that can be easily bypassed. Some of the methods include:

- Cell short circuit test – results may vary depending on the cell resistance
- Overcharge test – generally used for battery modules, not commonly used at cell level.

Figure 7 shows a typical setup for a cell short circuit test (top) and the result of the test (bottom). The degree of damage or thermal runaway depends on the cell capacity, internal resistance and external resistance that the setup adds.

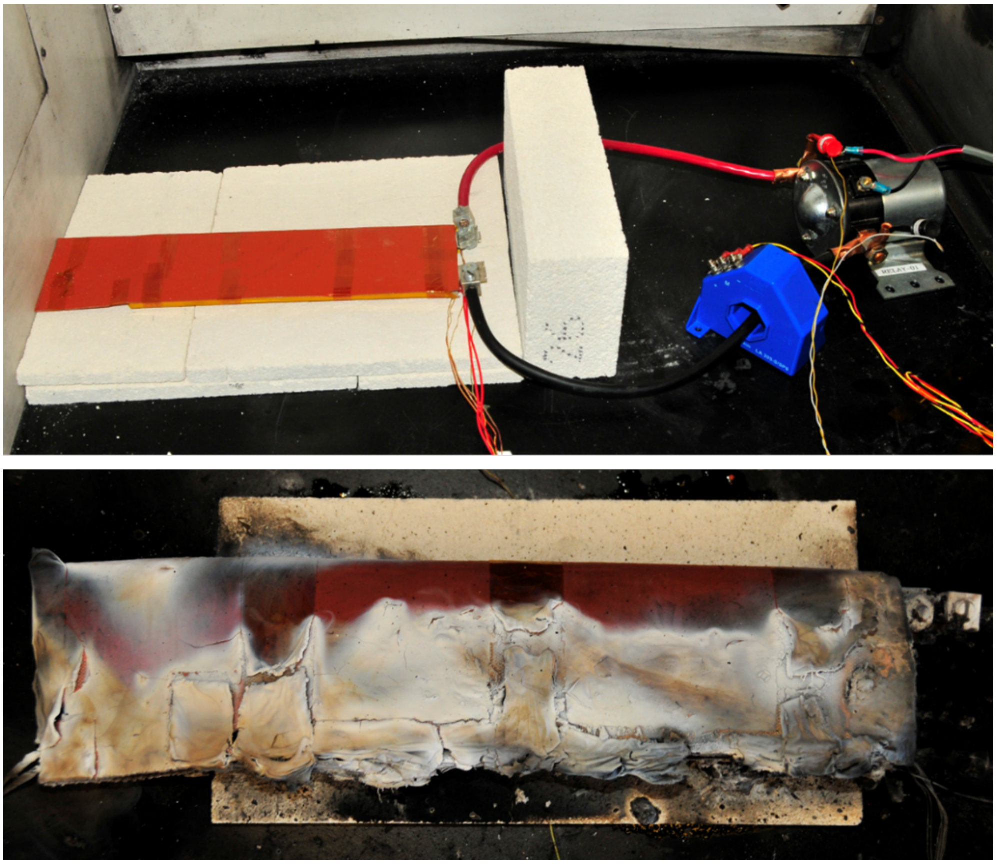

Figure 7 Cell Short Circuit Test

Other Techniques

Some of the other techniques discussed in the standards include inducing an internal short by introducing a contaminant within the cell. This technique requires specialized capabilities and can typically only be performed at the cell manufacturing sites. A few mechanisms have been proposed as being responsible for initiating an internal short due to foreign metal particle introduction [6]:

- Metal particle moves within the cell during charge/discharge cycles and punctures the separator causing a cell short
- Foreign metal particle dissolves in the cathode with subsequent plating of the metal on the anode which can result in dendrites and eventually puncture the separator causing a short.

The effect of this method depends largely on the size of the metal contaminant and its location within the cell. Single cell failure testing is the first step towards determining the effect of failure of a single cell within a battery system. Once the failure initiation method is tested, it is important to verify this method by performing system level testing. The larger scale of batteries in grid storage applications necessitates modeling of the system prior to actual testing to select the location of the single cell undergoing thermal runaway to simulate the worst-case condition. Although single cell failure tests provide an insight into the potential hazards that the cell thermal event may pose, in order to fully assess its effect at a system level, full-scale testing of the battery system including that of the ability of the system to limit and mitigate such a failure is necessary.

Each of the testing methods discussed above have its advantages and disadvantages when applied to a cell within a battery system. For example, using a heating method can result in unintentional heating of the neighboring cells and induce a more serious outcome. Mechanical techniques face challenges based on the battery enclosure design and may require customized testing setups.

Designing Larger Battery Systems

Single cell thermal runaway reactions in large battery systems are typically not spontaneous, although they almost always appear to be. As discussed in the sections above, these reactions can occur due to excessive heating over a period of time, electrical abuse over an extended period or latent manufacturing defects that may not manifest until later in the life of a cell. Hence, these failures should be accounted for in Failure Modes & Effects Analyses (FMEAs) and appropriate safety mechanisms and mitigation techniques should be incorporated in the design [1].

When designing a battery system, one of the considerations should be to make sure that the rate of heat dissipation within the system is fast enough such that the battery never reaches thermal runaway temperatures [7]. This includes designing an effective 'Battery Thermal Management System' (BTMS). An effective BTMS maintains the cell temperatures within an optimum range by using techniques like air-cooling or liquid-cooling.

Simulation and modeling of large battery systems during the design stage, before they are manufactured, gives an insight into a number of factors such as thermal mapping, structural integrity and insulation schemes. This helps reduce manufacturing costs, prevent frequent design changes and enhance safety. For example, prismatic or pouch cells have larger interface area between them when put together in a pack. Cylindrical cells tend to have less surface area in contact with neighboring cells. This can affect the temperature distribution between cells during cycling [2][8]. Modeling different cell configurations helps quantify this distribution and select the best configuration to avoid hot spots in the actual design.

Development of inherently safe cells by using specialized cell chemistries, non-flammable electrolytes and in-built safety mechanisms such as CIDs and PTCs helps reduce the probability of field failures. Regular audits of cell production lines can help identify the weaknesses early on and prevent inferior quality cells from being used. Designing a safe battery management system (BMS) is of utmost importance especially for large battery systems. Tools such as FMEA and Fault Tree Analysis (FTA) help identify the possible failure modes and recommend design and safety measures to mitigate them. Mechanical integrity of the battery system should be designed in a manner such that it restricts propagation of failure within the battery system and safeguards the surroundings and personnel involved.

Summary

This paper discusses some of the typical causes of field failures due to Li-ion batteries. Although rare, single cell failures can occur within battery systems and can result in hazardous outcomes and damage. Standards such as UL 1973 have recently incorporated discussions regarding tolerance to internal cell failure tests and the effect of propagation of these failures within a larger system. Some single cell failure techniques are discussed in the paper with examples of typical setups and results. Finally, the paper discusses a few design considerations for developing a battery system with a high degree of safety.

References

1. Single Cell Thermal Runaway Initiation (SCTRI) Test – (Propagation), Test Procedures developed by NHTSA to be shared with GTR, Pages 168 – 289, SAE International.
2. Lamb, Joshua, Orendorff, Christopher J., Steele, Leigh Anna M., and Spangler, Scott W. Failure propagation in multi-cell lithium ion batteries. United States: N. p., 2014. Web. doi:10.1016/j.jpowsour.2014.10.081.
3. Safety Issues for Lithium-Ion Batteries, UL LLC 2013
4. UL 1973 - Standard for Batteries for Use in Stationary, Vehicle Auxiliary Power and Light Electric Rail (LER) Applications, 2018
5. Arora, A., N. K. Medora, T. Livernois, and J. Swart, Safety of Lithium-Ion Batteries for Hybrid Electric Vehicles. In G. Pistoia (ed.), Electric and Hybrid Vehicles, Power Sources, Models, Sustainability, Infrastructure and the Market, Amsterdam: Elsevier, 2010, Chapter 18, pp. 463–491.
6. McCoy, C., et al, Implantation, Activation, Characterization and Prevention/Mitigation of Internal Short Circuits in Lithium-Ion Cells, 2012 DOE Annual Merit Review Meeting, May 2012.
7. Khan, M.R.; Swierczynski, M.J.; Kær, S.K. Towards an Ultimate Battery Thermal Management System: A Review. Batteries 2017, 3, 9.
8. Ouyang, D.; Liu, J.; Chen, M.; Weng, J.; Wang, J. Thermal Failure Propagation in Lithium-Ion Battery Modules with Various Shapes. Appl. Sci. 2018, 8, 1263.