A Review of Fire Mitigation Methods for Li-ion BESS

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BakerRisk's six-part series on Battery Energy Storage Systems (BESS) hazards is well underway, with the first two articles located here. The first two articles introduced us to BESS failure types and characteristics as well as failure rates while this article, the third in the series, is a review of fire mitigation methods for Li-ion BESS.

The global push for the transition to renewable energy has necessitated the need for efficient energy storage systems and Lithium-Ion Battery (LIB) based energy storage systems are the most prominent. LIB are in the forefront of battery technology due to their high energy density and other functional advantages and it is because of these advantages that LIB have rapidly replaced other battery types in multiple applications. Examples of such applications range from small personal electronic devices like cell phones to larger energy storage systems, also known as BESS, as used in electric vehicles as well as in renewable power generation such as solar or wind farms. While having many advantages, LIB carry an inherent risk of Thermal Runaway (TR), which may result in off-gassing (flammable, toxic, or explosive), fires, and explosion. This article focuses on various fire protection approaches to mitigate LIB fires in BESS.

The initiating events and common outcomes of a TR are shown in Figure 1, which is the most common failure mode of LIB. TR fires are fueled by an internal chemical reaction that releases heat and can continue without a supply of oxygen or a visible flame, unlike most conventional fires.[1] Additionally, the stored electrical energy and dense packing of modules in BESS presents significant challenges to mitigate battery fires. A photograph of a July 30th, 2021 TR fire on a battery pack in Moorabool, near Geelong, is shown in Figure 2.[2]

[1] Wang, Q., Mao, B., Stoliarov, S.I., et al., "A review of lithium ion battery failure mechanisms and fire prevention strategies," March 2019, Progress in Energy and Combustion Science

[2] https://www.abc.net.au/news/2021-09-28/fire-at-tesla-giant-battery-project-near-geelong-investigation/100496688

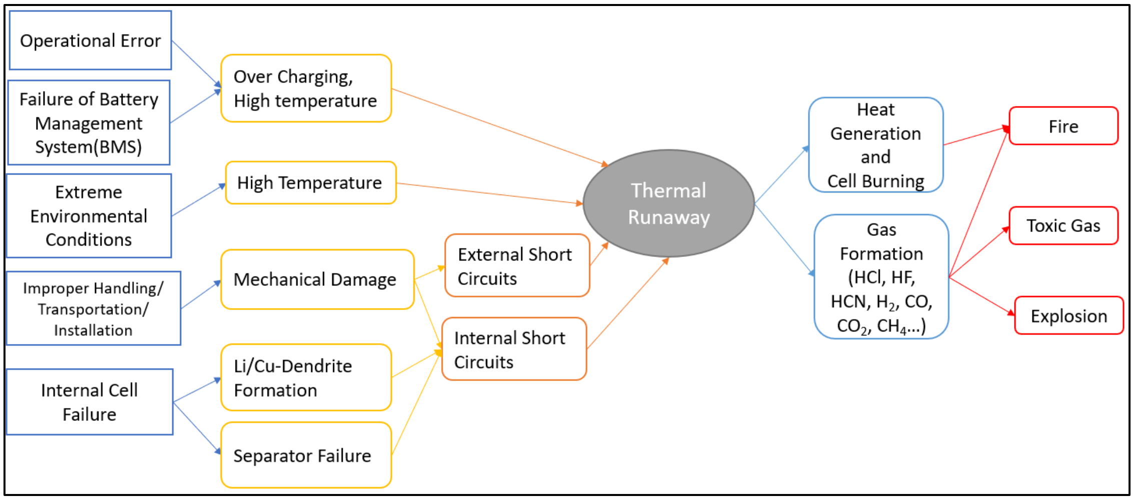

Figure 1. Li-ion Battery Thermal Runaway Schematic

Figure 2. Thermal Runaway Fire on a Battery Pack

The general arrangement of BESS, shown in Figure 3, is a crucial factor that aids thermal runaway propagation. The individual Li-ion cells are assembled into a module, modules are stacked together in racks, and finally a series of racks frame up to form the battery system. The heat generated from a single cell fire has the potential to initiate TR in adjacent cells. For large LIB BESS, this phenomenon can spiral into a cascading TR, affecting the entire module or the rack, and eventually the entire container as shown in Figure 4.

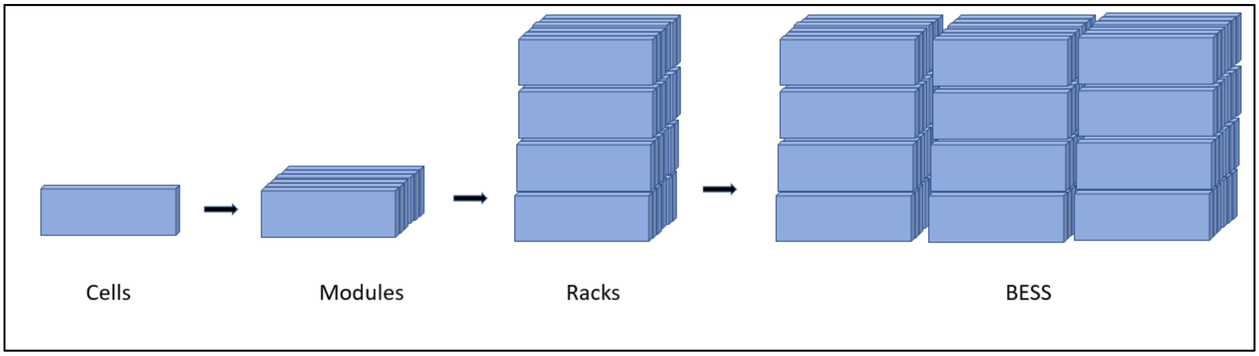

Figure 3. General BESS Arrangement

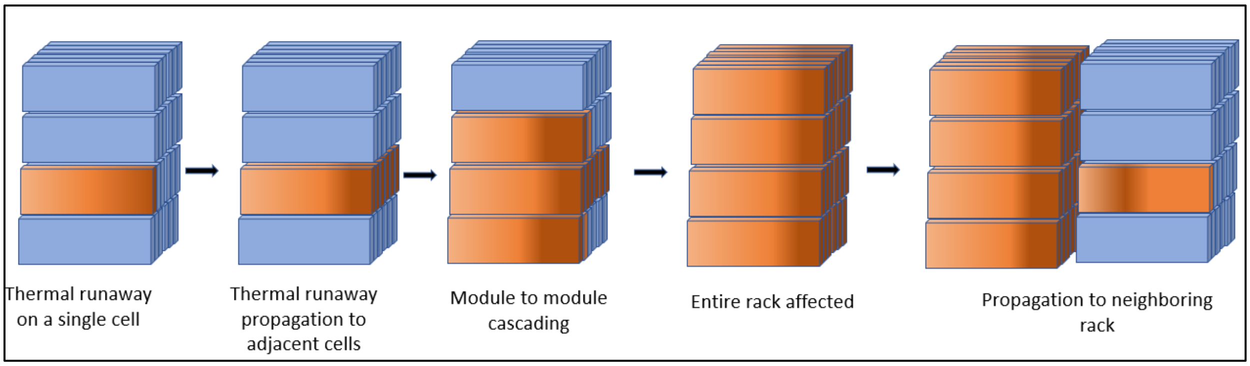

Figure 4. Thermal Runaway Propagation Phenomenon in a BESS

It is critical to note that heat propagation can be due to the heat generated inside the cell and/or flaming combustion of the released gases.[1] However, the major path of the thermal transfer within the battery module is due to the heat conduction through individual cell shells.[3]

Water-based automatic sprinkler systems are widely used for fire protection of general commodities owing to the effective cooling properties of water. However, effectiveness of water-based fire protection systems for LIB-based BESS fires needs to be investigated. At present, there is a gap in data from full-scale fire and suppression testing showing the overall effectiveness of water-based systems on suppression of LIB-based BESS fires.[4] Some of the impediments of water-based fire protection are as follows:

- The high conductivity of water may cause short circuiting of cells presenting collateral damage risk.
- High volume of water is required to cool the cells below the critical temperature to prevent TR propagation.[5]

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3 Feng X., Sun J., Ouyang M., et al., "Characterization of penetration induced thermal runaway propagation process within a large format lithium ion battery module," February 2015.

4 Mikolajczak, C., et al., "Lithium-Ion Batteries Hazard and Use Assessment." The Fire Protection Research Foundation, July 2021.

5 Zhang, L., Duan, Q., et al., "Experimental Investigation of Water Spray on Suppressing Lithium-Ion Battery Fires," Fire Safety Journal, March 2021.

- The application of water on a LIB fire increases the generation of off-gases such as CO, H_2 and HF. Applying water causes incomplete combustion of organic substances inside the battery resulting in production of CO rather than CO_2; when water is applied, H_2 is released without combustion, increasing its concentration; and water reacts with phosphorus pentafluoride to produce HF.
- Due to the dense packing of modules, the inability of water to cool the cell interiors may result in re-ignition of a fire once the water application is halted.

Water mist systems with droplets of size in the magnitude of 1000 microns (traditional water spray systems have a droplet size around 5,000 microns) are gaining traction. Lab-scale tests show that adding surfactants and gelling agents to the water mist system decreases the amount of water required to suppress fires and effectively cool adjacent modules.[6] The initial promising results are pushing many LIB manufacturers to recommend water-based systems despite their known disadvantages.

LIB high voltage components may require inert gas application, for example CO_2 or N_2, or halocarbon based clean agents.[7] Gaseous agents are traditionally preferred for electrical systems because of their low conductivity and negligible residue (batteries do not get wet!). When activated by an off-gas or smoke detection system, application of inert gases in an enclosed environment reduces the O_2 concentration, which helps extinguish the fire, also known as smothering. While the gaseous agents can penetrate to deep-seated LIB fires unlike water-based systems, the poor cooling properties of gases in general make them ineffective in preventing TR propagation.

Halocarbon-based clean agent systems, for example Novec 1230 or FM-200, may be capable of suppressing incipient LIB fires when activated with early detection. Halocarbon-based clean agents extinguish fires by breaking the chain reaction of combustion. Note that a significant downside of gaseous agents such as CO_2 and N_2 is the asphyxiation hazard, the major disadvantage of halocarbon-based agents is the potential to form secondary toxic and corrosive products when exposed to high temperatures.[1]

Currently, no one fire protection approach alone is a solution for LIB-based BESS fires. For instance, the halocarbon-based clean agents or inert gas systems are not adequate to prevent a cascading TR, and the water-based system is ineffective at reaching deep-seated cell fires, which also increases the risk of damaging the unaffected cells by external short circuiting. Additionally, both systems produce toxic off-gases when applied to a LIB fire.

A multi-layer protection strategy that includes early detection and suppression may be the best alternative. Since each BESS has its own unique battery chemistry, with different arrangements of battery modules and facility-specific emergency response strategies, a case-by-case approach is vital to design fire protection for large-scale LIB-based BESS. A combination of protection layers capable of suppressing

[6] Mohammadmahdi, G., et al., "A Review of Lithium-Ion Battery Fire Suppression," October 2020
[7] Clean Agent is volatile or gaseous fire extinguishing system that is electronically non conducting and that does not leave a residue upon evaporation- NFPA 2001: Standard on Clean Agent Fire Extinguishing Systems (2018 Edition)

battery fire, preventing propagation of TR, and managing the concentration of resulting off-gas may be the best path forward until a fully tested and validated BESS-specific fire mitigation technology emerges.

BakerRisk is interested in collaborating with industry partners to perform testing of various fire protection strategies for LIB systems and encourages interested parties to join. BakerRisk has performed similar tests on both large and small scales for flammable liquids and vapors.[8]

[8] Gandhi, M., et al., Fire Protection Research Foundation Report: "Vapor Mitigation Testing Using Fixed Water Spray System." April 2019.