THE DIFFERENCE BETWEEN THERMAL RUNAWAY AND IGNITION OF A LITHIUM ION BATTERY

December 2022

Thermal runaway is not ignition. In the simplest terms, thermal runaway refers to the irreversible failure of a lithium ion battery that leads to the production of flammable gases. There are many abuse conditions that can trigger thermal runaway, including short circuits, mechanical damage, overcharging or over discharging, and overheating [1, 2, 3]. Thermal runaway could lead to two consequences:

1. Ignition of the unmixed flammable gases can result in a fire.
2. Ignition of the flammable gases mixed with air, often in a confined environment, can lead to an explosion.

A thermal runaway process occurs when the heat generated by exothermic reactions is greater than the heat dissipated to the environment [4]. As depicted in Figure 1, for a lithium ion battery this can start when the solid-electrolyte interphase (SEI) layer breaks down. SEI is a passive, stabilizing layer that forms over the anode surface due to electrochemical incompatibility between the anode and electrolyte. The SEI layer prevents continued electrolyte degradation at the anode surface. As the temperature in the cell increases, this layer breaks down and releases carbon dioxide. The carbon dioxide acts as an ionic and thermal insulator, causing the cell to produce more heat as it tries to complete electrochemical reactions.

When the SEI layer breaks down under abuse conditions, the electrolyte is exposed to the anode surface. That prompts regeneration of the SEI layer and additional decomposition, which moves the thermal runaway process along. Flammable hydrocarbons are produced, and the cell continues to generate heat. Eventually, the heat accumulated in the cell leads to increased temperature, which causes the polymer film separator to melt, allowing for an internal short circuit to occur and more heat production.

As temperatures rise, the cathode starts to break down and release oxygen. The electrolyte solvents react with the oxygen to form carbon dioxide, fluoride gases, and other hydrocarbons. Finally, the polymer binder material used to fabricate the electrodes also breaks down and releases hydrogen fluoride gas [4, 5].

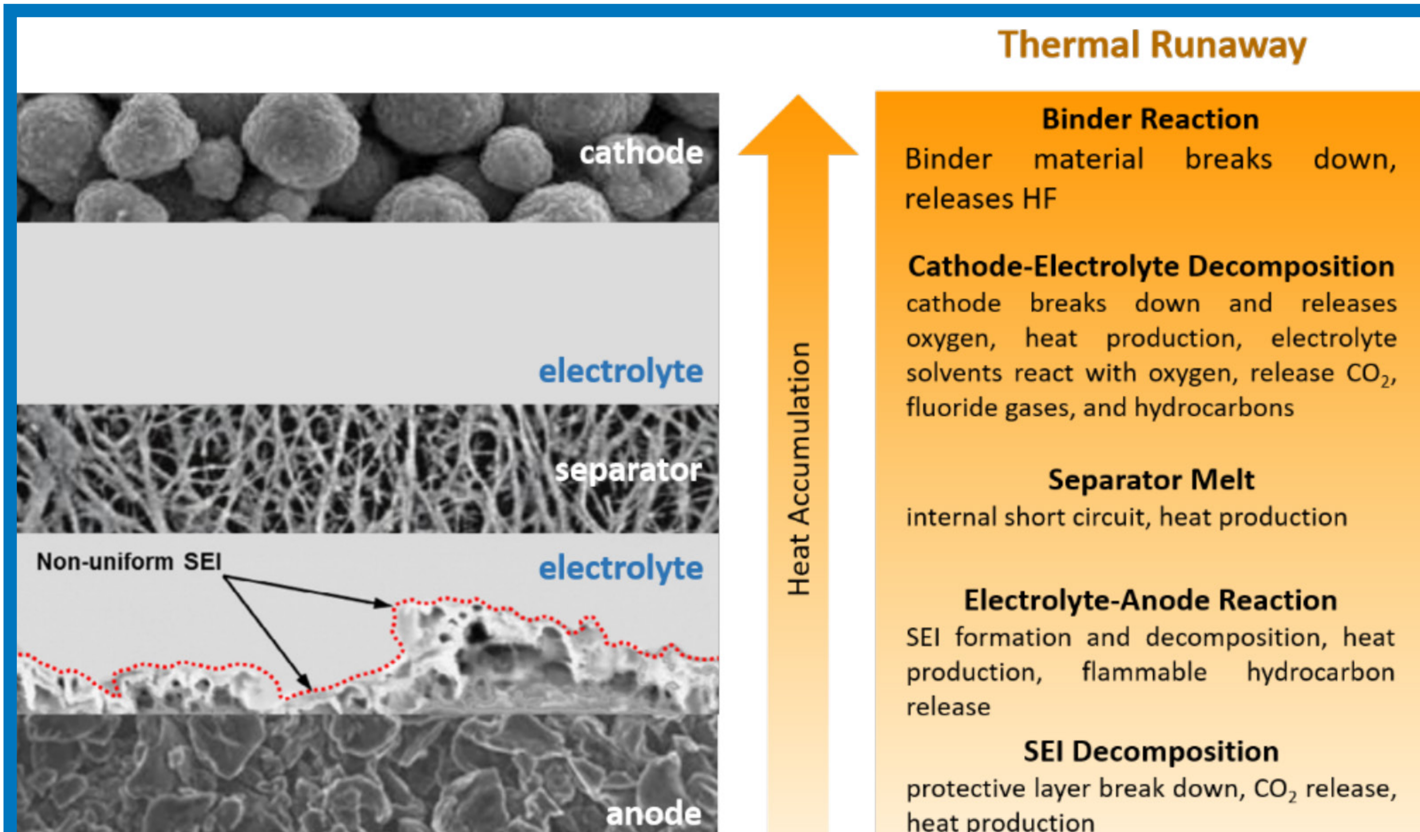
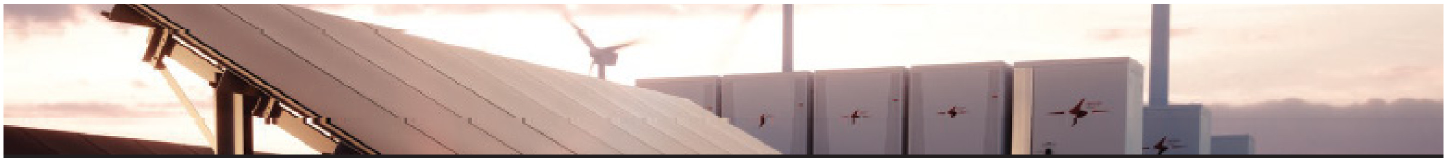


Figure 1 – Depiction of a common thermal runaway process. Image courtesy of EPRI



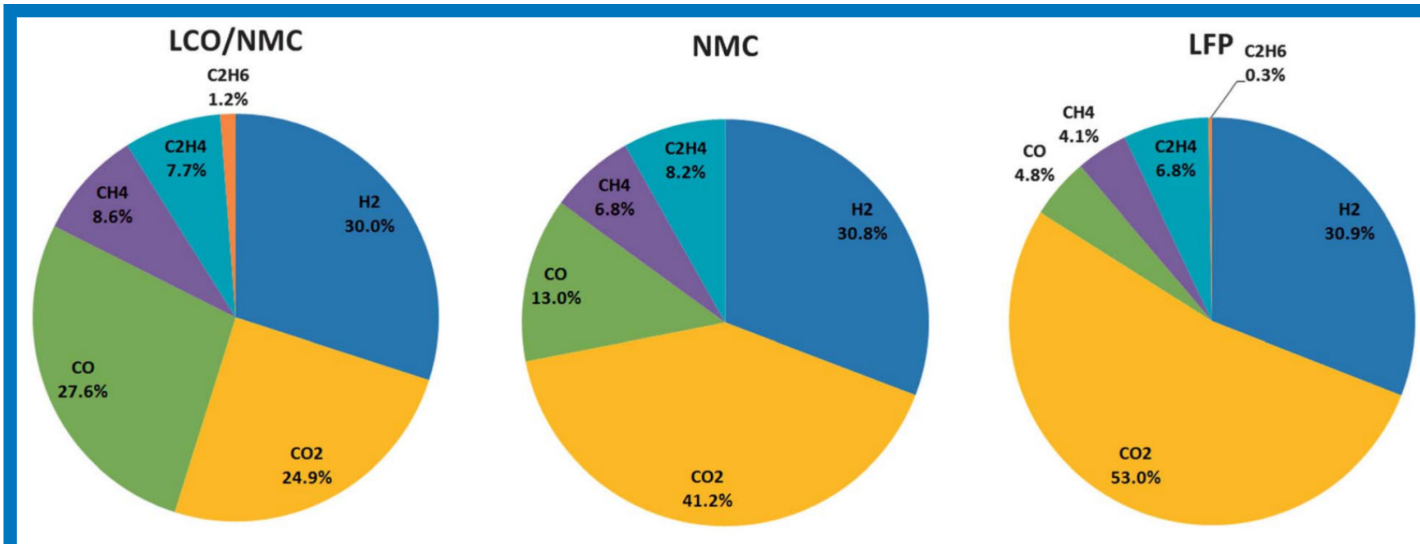


Figure 2 – Detected components of the produced gases (mol%) [6]. Image is licensed under CC BY 3.0.

The thermal runaway process causes cell pressure to increase as the materials break down and expand. Hot aerosols and flammable gases are ejected from the battery at high speeds [4]. Figure 2 depicts the composition of battery vent gases collected from lithium ion batteries with different chemistries. Carbon monoxide, methane, ethylene, ethane, and hydrogen gas were detected across the various chemistries and all these gases are flammable [6]. The mixture of gases ejected could ignite under the right conditions [7].

Oxygen would be provided by the surrounding environment. The fuel and air mixture needs to be within the lower and upper flammability limits (LFL and UFL) for combustion to occur. The gas composition will determine key flammability properties including the LFL and burning velocity [7].

Batteries can undergo thermal runaway without subsequent fire. This observation is evident to anyone who has seen a cell phone battery pouch expand like a balloon, shown in Figure 4. Lab-scale testing in inert environments has been performed to quantify vent gas composition in the absence of flames [8]. The McMicken BESS incident in Surprise, AZ also demonstrated thermal runaway without ignition. A single battery rack had undergone thermal runaway, filling the container with flammable gas. The flammable gas/air mixture was initially too rich to burn. First responders arrived at the site and opened the container doors to investigate the failure. By doing so, they introduced enough oxygen into the environment and the heat inside the container ignited the gases [7]. The uncertainty

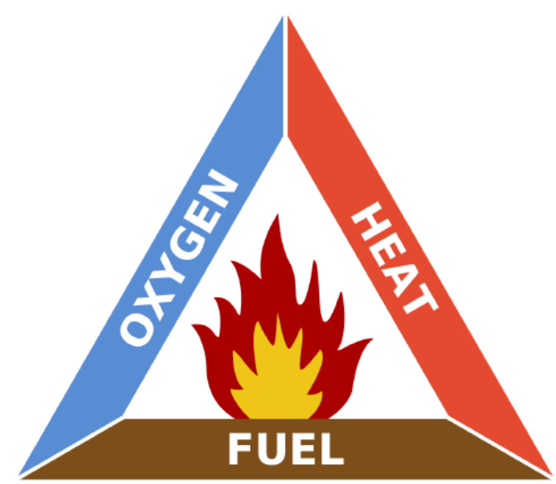


Figure 3 – "Fire triangle" by Gustavb is licensed under CC-BY-SA 3.0

of ignition was later encountered during testing at FM Global, Figure 5, where abuse testing of identical lithium ion battery modules showed that ignition of vented gases can be unpredictable even in a controlled laboratory setting [9].

The U.S. has seen rapid adoption of energy storage within the past decade with lithium ion technologies accounting for the majority of deployed capacity, seen in Figure 6. Lithium ion batteries present many favorable factors that contribute to this trend including cost, maturity, roundtrip efficiency, and flexibility.

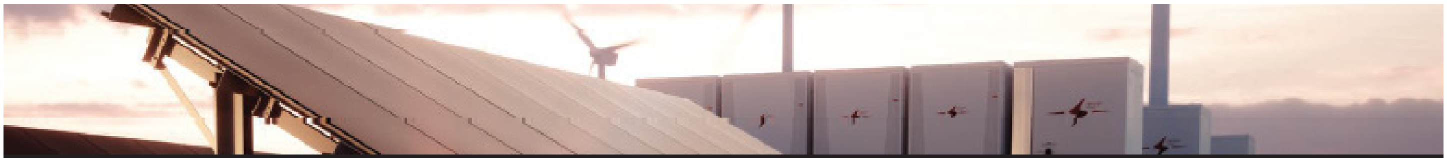


Figure 4 – Side-by-side comparison of a lithium ion polymer pouch cell that has undergone the onset of thermal runaway (left) and an undamaged cell (right) [10]. Image courtesy of Appuals.

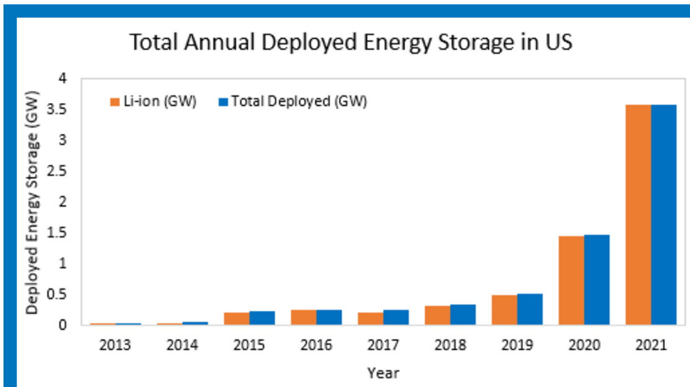


Figure 6 – Annual deployed energy storage in the US. Excludes Pumped Hydro Storage. [11].

The number of lithium ion battery energy storage failures is expected to increase with growing technology adoption. As of December 2022, EPRI's Battery Energy Storage System (BESS) Failure Event Database has recorded 56 stationary energy storage failure events across the globe since 2011; 49 of those events have occurred since 2018. In the US, there have been five incidents this year, an increase compared to the three incidents recorded in 2021 [12].

The statistics around thermal runaway occurrences vary and data collection to produce meaningful information is difficult. Assuming lithium ion battery cells are stored and operated within the recommended limits provided by the manufacturer, the rate of failure over the cell's lifetime has been estimated to be 1 in 10 million per a 2006 source or 1 in 40 million per a 2011 source [4, 13]. These statistics need to be updated, especially given that the actual rate of failure will be heavily influenced by unpredictable circumstances

Figure 5 – Lithium ion battery module thermal runaway leading to flammable gas release (left) and fire (right). Images courtesy of FM Global. Testing involved overheating of lithium iron phosphate cells without the presence of an external ignition [9].

that could be classified as electrical, thermal, or mechanical abuse of the system. Furthermore, the sheer number of cells deployed means that failures are not only possible but will become more frequent. One representative electric car battery using 18650 type lithium ion cells can have ~8,000 cells. Assuming a failure rate of 1 in 40 million cells, nearly 1 in every 5,000 representative vehicles

could fail due to a battery manufacturing defect over the product's lifetime. The number of cells in a stationary energy storage system will vary more depending on the size and form factor of the cells. The McMicken battery in Arizona (2MW/2MWh) had 10,584 cells [14], SCE's Mira Loma battery (20MW/80MWh) has 6,465,720 cells [15], and Vistra's Moss Landing Phase 1 (300MW/1200MWh) system has roughly 5,544,000 [16].

Thermal runaway is a major factor contributing to the fire and explosion risk that needs to be considered during all stages of system design. While this is often initially managed with battery and thermal management systems, newer installed systems may also include gas detection and ventilation to prevent fire and explosion if thermal runaway occurs. With enough research, the potential for subsequent fire and explosion may be controllable with proper system design and management but eliminating the threat of thermal runaway may remain a challenging goal.

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Energy Storage

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3002025283 December 2022

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